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# SIGNIFICANCE OF NEARSHORE TRACE-FOSSIL ASSEMBLAGES OF THE CAMBRO–ORDOVICIAN DEADWOOD FORMATION AND ALADDIN SANDSTONE, SOUTH DAKOTA

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## Abstract

The Cambro–Ordovician Deadwood Formation and Aladdin Sandstone represent intertidal and subtidal, nearshore deposystems that contain few well-preserved body fossils, but contain abundant trace fossils. The present study uses the much neglected trace-fossil fauna to describe the diverse paleoenvironments represented in the Deadwood–Aladdin deposystems, and to better understand the environmental conditions that controlled benthic life in the Early Paleozoic.

The Deadwood–Aladdin ichnotaxa can be separated into three distinct assemblages based on the changing sedimentologic and hydrodynamic conditions that existed across the Cambro–Ordovician shelf. Trace-fossil assemblages and corresponding lithofacies characteristics indicate that the Deadwood–Aladdin deposystems formed within an intertidal-flat and subtidal-shelf environment.

Based on the distribution and numbers of preserved ichnotaxa, the intertidal flat can be subdivided further into an ecologically stressful inner sand-flat environment, and a more normal marine outer sand-flat environment, both of which belong to a mixed, *Skolithos–Cruziana* softground ichnofacies. The inner sand flat is characterized by low diversity, low numbers, and a general lack of complexly constructed ichnotaxa. Trace fossils common to both assemblages tend to be smaller in the inner flat compared to the outer sand flat. Taphonomic effects, such as substrate type and sediment heterogeneity, also aid in differentiating between the inner and outer sand-flat assemblages.

The subtidal shelf environment is categorized in the *Cruziana* ichnofacies. Ichnological evidence of periodic tempestite deposition and hardground development within this subtidal regime is manifested by high diversity and low abundance of ichnogenera.

Key Words: trace fossils, ichnofossils, Cambrian, Ordovician, South Dakota, ichnofacies

## Introduction and Historical Perspective

The Deadwood Formation and Aladdin Sandstone comprise all the Upper Cambrian and most of the lowermost Ordovician rocks in western North Dakota and South Dakota, and eastern Montana and Wyoming. Surface exposures are limited to the Black Hills region of western South Dakota and eastern Wyoming, where they form an elliptical outcrop pattern within the interior of the Black Hills uplift (Fig. 1).

The Deadwood Formation was formally named by Darton (1909) for exposures at Deadwood, South Dakota. The stratotype included the Deadwood Formation, Aladdin Sandstone, and basal lithotypes of what is now known as the lowermost Ordovician Winnipeg Formation (Fig. 1, 3). Because of the paucity of body fossils, Darton (1909) could only ascribe a Cambrian age to the type section. With continued paleontologic study of enclosed trilobites, the "Deadwood Formation"

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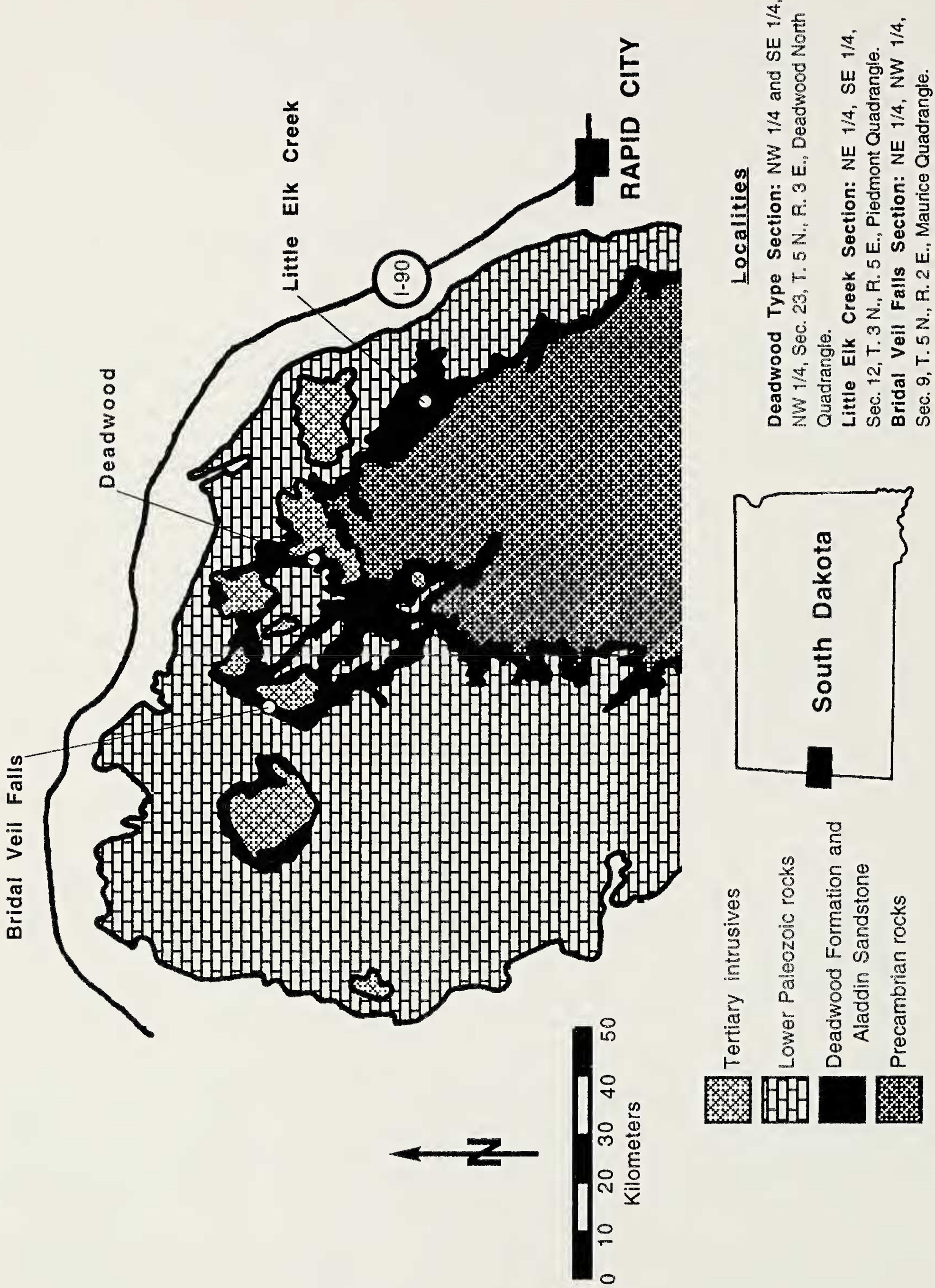
Bridal Veil Falls
Deadwood
Little Elk Creek
I-90
RAPID CITY
South Dakota
Localities
Deadwood Type Section: NW 1/4 and SE 1/4, NW 1/4, Sec. 23, T. 5 N., R. 3 E., Deadwood North Quadrangle.
Little Elk Creek Section: NE 1/4, SE 1/4, Sec. 12, T. 3 N., R. 5 E., Piedmont Quadrangle.
Bridal Veil Falls Section: NE 1/4, NW 1/4, Sec. 9, T. 5 N., R. 2 E., Maurice Quadrangle.
N
0 10 20 30 40 50
Kilometers
Tertiary intrusives
Lower Paleozoic rocks
Deadwood Formation and Aladdin Sandstone
Precambrian rocks

was given a Late Cambrian age by Darton and Paige (1925). Later, Furnish et al. (1936) separated the overlying Winnipeg Formation from the Deadwood Formation based on the presence of Early Ordovician conodonts. Subsequently, Lochman and Duncan (1950) found Early Ordovician trilobites in the upper intraclastic limestones in several "Deadwood" sections. Because no obvious unconformity exists between Cambrian and Ordovician strata, the Deadwood Formation was reassigned a Late Cambrian–Early Ordovician age. The current stratigraphic picture was completed by McCoy (1952) who designated the upper 4.4 m of the Deadwood Formation as the Aladdin Sandstone based on the presence of numerous *Skolithos* burrows.

Since its first description, investigators of the Deadwood Formation have commented on the abundant trace fossils that occur within the unit (Darton, 1909; Darton and Paige, 1925). Although trace fossils represent the dominant faunal evidence within the Deadwood Formation, paleontological and paleoecological studies have been limited to the meager occurrences of trilobites and inarticulate brachiopods (Lochman-Balk, 1964, 1970, 1971). Only one taxonomic study has dealt directly with the Deadwood–Aladdin trace fossils, and that was the designation of a new ichnogenus, *Ixalichnus*, by Callison (1970). Consequently, this present work addresses not only the systematic ichnology, but also the paleoenvironmental and paleoecological aspects of the Deadwood–Aladdin ichnofauna.

The institutional abbreviation used in text is KSU, Kent State University, Kent, Ohio.

### *Regional Paleogeography*

Throughout most of the Late Cambrian and Early Ordovician, two major facies belts developed across the cratonic shelf (Palmer, 1960; Fig. 2). In the region of the Black Hills, the Deadwood Formation and Aladdin Sandstone were deposited within the inner detrital belt, representing marginal–marine deposition. The transcontinental arch was the dominant tectonic element during much of the Paleozoic, and greatly influenced the type and distribution of the Deadwood–Aladdin deposystems (Lochman-Balk and Wilson, 1967). As with many deposits of this time, initial submergence of the Cambrian shelf in the Black Hills area occurred on Precambrian basement composed principally of schists and metaquartzites. Topographic relief on the basement surface consisted of metaquartzite monadnocks averaging no more than 30 m high. During the initial marine transgression into the Black Hills region these monadnocks became sources of metaquartzite boulders deposited as the basal conglomerate of the Deadwood Formation (Lochman-Balk and Wilson, 1967). Continued encroachment of the Cambro–Ordovician seas eastward was largely impeded by the transcontinental arch, which also supplied most of the terrigenous sediment of the inner detrital belt. The Black Hills area also was undergoing continual epeirogenic uplift throughout the Paleozoic, and may have represented a distal arm of the transcontinental arch (Gries, 1975).

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Fig. 1.—Generalized geologic map of the northern Black Hills in western South Dakota and eastern Wyoming. Outcrop pattern of the Deadwood Formation and Aladdin Sandstone shown as black band bounded by Precambrian basement and Lower Paleozoic carbonates. Location of measured sections are indicated by the white circles, and township and range coordinates for sections are given in lower left of this figure.

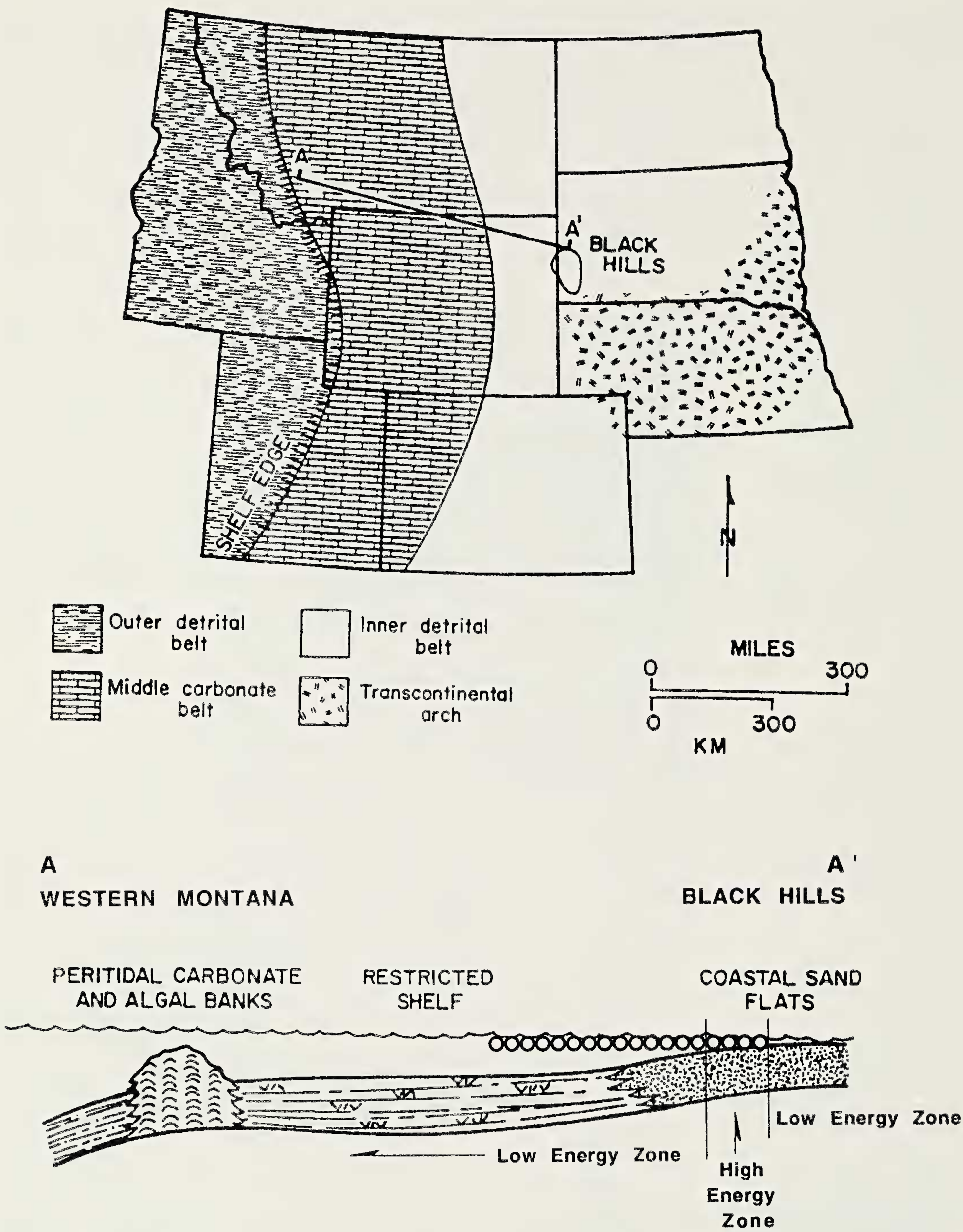



Fig. 2.—Paleogeographic map of the Cambro–Ordovician craton showing relative positions of the shelf edge and transcontinental arch, and lateral distribution of major facies belts. Cross-section A–A′ shows basic depositional environments across the cratonic shelf, superimposed with Irwin's (1965) model of epeiric sedimentation, and distribution of energy zones in nearshore cratonic settings. The high energy zone in Irwin's (1965) model corresponds to lithofacies 2 and 4 of the Deadwood Formation and Aladdin Sandstone. Small circles on cross section represent zone of effective wave base. Diagram modified from Palmer (1960) and Sepkoski (1982).

Continual epeirogenic upwarping is suggested by a general thinning of Paleozoic strata as they onlap the Black Hills region (Gries, 1975; Lisenbee, 1975). Farther to the west, rocks characteristic of nearshore coastal deposystems of the Deadwood Formation grade into restricted subtidal-shelf deposystems of the middle carbonate belt, represented by Deadwood time-equivalent units of the Du Noir and Emerson formations of Wyoming and Montana (Miller, 1936; Sepkoski, 1982; Fig. 2). Both formations are composed of thick shale and intraclastic limestone sequences, lithologically similar to the middle parts of the Deadwood Formation (Fig. 3), and indicate that shelf-like conditions extended into the Black Hills during times of maximum transgression. However, open-ocean circulation across the shelf was restricted by algal buildups along the shelf margin (Sepkoski, 1982; Fig. 2). West of the algal banks, restricted shelf sedimentation of the middle carbonate belt abruptly grades into outer-shelf and shelf-slope sedimentation of the outer detrital belt (Palmer, 1960).

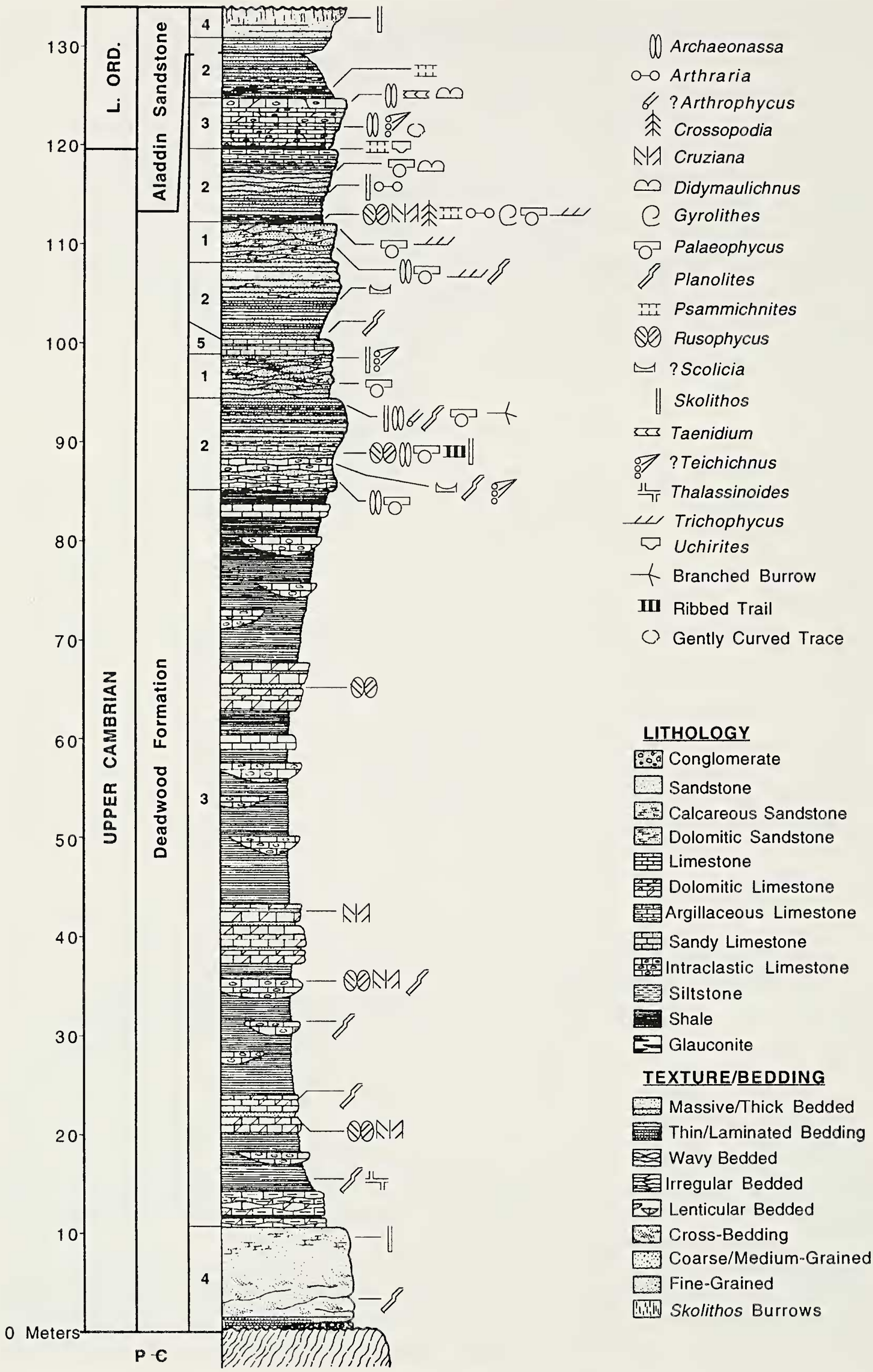
### *Deadwood and Aladdin Lithofacies*

In the northern Black Hills (Fig. 1), five lithofacies were deposited throughout Cambro–Ordovician time in this region. These are: 1) irregularly bedded hematitic sandstones, 2) interbedded sandstone and siltstones, 3) interbedded shale and intraclastic limestones, 4) crossbedded sandstones, and 5) hematitic sandy limestones (Fig. 3, 4; Table 1).

*Irregularly Bedded Hematitic Sandstone Lithofacies (Lithofacies 1).*—Lithofacies 1 is characterized by dark reddish brown, medium-grained sandstone, with minor reddish green shale partings at the base. Bedding thickness is highly variable and irregular, ranging from thin-bedded (3–5 cm) to thick-bedded (25–66 cm) intervals. Bed thickness increases toward the top of the lithofacies. Primary sedimentary structures are rare within thick-bedded strata, but consist of multidirectional ripple marks and small-scale crossbed sets in the thin-bedded intervals. Glauconite is a minor constituent of the sandstone although hematite is rather abundant, giving the facies its characteristic red color. Dolomite and calcite alternate as the main cements, with calcite being predominant in the basal parts of the lithofacies.

*Interbedded Sandstone and Siltstone Lithofacies (Lithofacies 2).*—Lithofacies 2 is composed predominantly of light-colored, interbedded fine-grained sandstone and siltstone beds that are 0.5–2.0 cm thick. Current laminations, wavy crossbedding showing multiple current directions, parting lineations (Fig. 7D), and current-rippled bedding surfaces are common. Mudcracked surfaces also occur on some of the siltstone beds. Subordinate lithologies include shale as thin partings and clay drapes between sandstone and siltstone beds, which produced a flaser bedding texture, and fine-crystalline argillaceous limestone intervals normally found in the basal and upper parts of the lithofacies. Distinct grains or lenticular patches of glauconite are common within the sandstones and siltstones. Calcite is the dominant cement throughout. This facies represents the best exposed and most easily recognizable lithotype of the Deadwood Formation, and totally incorporates the lower 2.4 m of the overlying Aladdin Sandstone (Fig. 3).

*Interbedded Shale and Intraclastic Limestone Lithofacies (Lithofacies 3).*—Lithofacies 3 is composed of thin-bedded (3–10 cm), lenticular intraclastic limestone interbedded with thick (1–7 m) intervals of fissile shale, and thin-bedded (1–30 cm), finely crystalline to micritic limestone. Intraclasts are normally oblate



130
120
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90
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30
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L. ORD.
UPPER CAMBRIAN
Aladdin Sandstone
Deadwood Formation
P-C
Archaeonassa
Arthraria
?Arthrophycus
Crossopodia
Cruziana
Didymaulichnus
Gyrolithes
Palaeophycus
Planolites
Psammichnites
Rusophycus
?Scolicia
Skolithos
Taenidium
?Teichichnus
Thalassinoides
Trichophycus
Uchirites
Branched Burrow
Ribbed Trail
Gently Curved Trace
LITHOLOGY
Conglomerate
Sandstone
Calcareous Sandstone
Dolomitic Sandstone
Limestone
Dolomitic Limestone
Argillaceous Limestone
Sandy Limestone
Intraclastic Limestone
Siltstone
Shale
Glauconite
TEXTURE/BEDDING
Massive/Thick Bedded
Thin/Laminated Bedding
Wavy Bedded
Irregular Bedded
Lenticular Bedded
Cross-Bedding
Coarse/Medium-Grained
Fine-Grained
Skolithos Burrows

to tabular in shape, and set within a fine-grained crystalline or micritic limestone matrix. No current orientation of the intraclasts was evident. Upper surfaces of the intraclastic limestones commonly were cracked, pitted, and accompanied by protrusion of intraclasts above the bedding surface, suggesting possible hardground or firmground development from early subaqueous cementation (Leeder, 1982:291), or from exposure of partially lithified sediments from periodic storm erosion (Bromley, 1990:19). Lower contacts of intraclastic limestones were curved or appeared erosive into the underlying shale lithologies. Shale intervals are composed of gray, black, green, and sometimes purple calcareous fissile (1–4 mm thick) shale, along with subordinate amounts of lenticular-bedded calcareous siltstone.

*Crossbedded Sandstone Lithofacies (Lithofacies 4)*.—Lithofacies 4 is composed of a basal trough crossbedded sandstone and conglomerate facies deposited in a high-energy, nearshore beach or barrier island system, that encompasses the basal 10 m of the Deadwood Formation, and supports a meager and poorly preserved trace-fossil assemblage consisting of *Skolithos* and scant *Planolites*(?) burrows. This lithofacies also characterizes the upper 1.5–2 m of the Aladdin Sandstone, which exhibits the typical *Skolithos* ichnofabric of lower Paleozoic orthoquartzites (Droser, 1991; Droser and Bottjer, 1993). Because of the density of the *Skolithos* burrows, this upper part of the Aladdin has an average ichnofabric index of 4 based on Droser and Bottjer (1993). Both the sedimentological and ichnological nature of lithofacies 4 support a high-energy interpretation for this lithofacies (Droser and Bottjer, 1989; Bockelie, 1991; Droser, 1991).

*Hematitic Sandy Limestone Lithofacies (Lithofacies 5)*.—Lithofacies 5 is composed of a wavy bedded, very argillaceous to sandy, hematitic, crystalline limestone that contains no trace fossils. Laterally, this lithofacies is discontinuous, but is always associated with lithofacies 1 or 2, and is interpreted to have formed on an intertidal carbonate flat in areas undergoing relatively low siliciclastic influx (Fig. 4).

Because of the importance of their enclosed trace fossils, only lithofacies 1, 2, and 3 will be discussed in detail in the following sections. All three of these main lithofacies types fall within the typical Seilacherian, marine softground ichnofacies (Bromley, 1990:215; Bromley and Asgaard, 1991).

## SYSTEMATIC ICHNOLOGY

Of the 18 formally designated ichnogenera and 27 ichnospecies collected from the Deadwood and Aladdin formations, ten ichnogenera are diagnostic for paleoenvironmental interpretations due to their restricted occurrences (Fig. 3, 16; Table 1). Ichnotaxa important in paleoenvironmental interpretations include *Archaeonassa*, *Skolithos*, *?Scolicia*, *Gyrolithes*, and *Arthraria* in differentiating outer sand-flat environments from inner sand flats and the subtidal shelf. The presence of certain ichnospecies, such as *Planolites beverleyensis* and *Palaeophycus tubularis*, can also aid in differentiating the inner sand flats from the outer sand flats.

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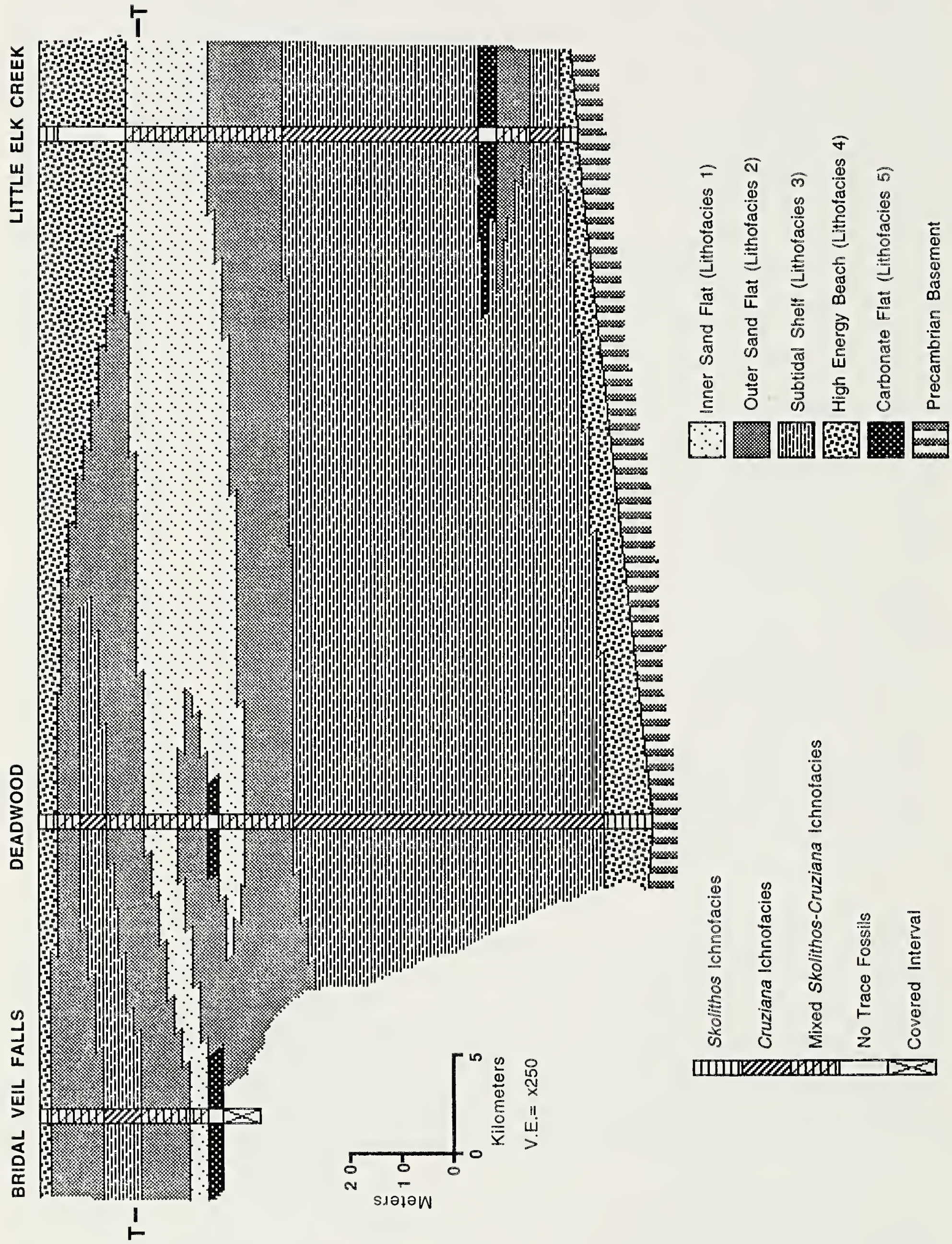
Fig. 3.—Composite weathered profile of the Deadwood Formation and Aladdin Sandstone showing lithofacies and stratigraphic distribution of the collected trace fossils. Numbers to left of section correspond to lithofacies types described in text.


BRIDAL VEIL FALLS
DEADWOOD
LITTLE ELK CREEK
T
T
Meters
2 0
1 0
0
0
5
Kilometers
V.E.= x250
Skolithos Ichnofacies
Cruziana Ichnofacies
Mixed Skolithos-Cruziana Ichnofacies
No Trace Fossils
Covered Interval
Inner Sand Flat (Lithofacies 1)
Outer Sand Flat (Lithofacies 2)
Subtidal Shelf (Lithofacies 3)
High Energy Beach (Lithofacies 4)
Carbonate Flat (Lithofacies 5)
Precambrian Basement

Ichnogenera such as *Cruziana*, *Rusophycus*, *Crossopodia*, and *Didymaulichnus* are more indicative of the subtidal shelf environments.

Ichnogenus *Archaeonassa* Fenton and Fenton, 1937
*Archaeonassa fossulata* Fenton and Fenton, 1937
(Fig. 5A–C)

*Material Examined.*—*Archaeonassa fossulata* is one of the most common traces collected, being found at all three measured sections. Only two are illustrated showing the range in both morphology and preservation. A large slab (KSU 4556) with over ten individuals was collected at the Deadwood type locality. KSU 4597 was collected at the Little Elk Creek locality.

*Description.*—Straight to gently curving, trace preserved in concave epirelief; width 2–5 mm, maximum length 110 mm; trace consists of a smooth to transversely striated groove, bounded by variably defined lateral ridges; groove typically three-fourths total trace width, semicircular in cross section; bounding ridges smooth, ranging from sharp-crested to broadly-rounded semicircles in cross section; ridges are as high as groove is deep; trace may tangently intersect shallow, circular depression averaging 15 mm in diameter and no more than 5 mm deep.

*Discussion.*—A much needed taxonomic review of *Archaeonassa* has been done by Buckman (1994). The Deadwood forms conform to two of Buckman's preservational variates, the smooth and standard type, of *A. fossulata* (Buckman, 1994:188, text-fig. 5A, B2), with the smooth variate being the more common of the two forms. The ichnogenus has been attributed to the locomotor activities of gastropods, trilobites, and even irregular echinoids (Fenton and Fenton, 1931, 1937; Buckman, 1994). Concerning the Deadwood material, echinoids may be excluded as potential trace makers, because they did not evolve until the Late Ordovician. Although trilobites cannot be entirely excluded as possible excavators of the Deadwood *Archaeonassa*, they seem unlikely given that *A. fossulata* is a true epirelief trace in construction (Buckman, 1994). Trilobite repichnion, such as *Cruziana*, are rarely preserved as epireliefs (Seilacher, 1970; Goldring, 1985). Gastropods seem to be the best candidates as trace makers, based on observations of trails left by the Recent snails *Littorina* and *Ilyanassa* on intertidal and subtidal flats in Washington and California (Fenton and Fenton, 1931, 1937). Important to this interpretation is that the Recent snails would occasionally excavate a small circular depression, terminating the epichnial groove. The Deadwood specimens of *Archaeonassa* imply a similar behavior as some of the trails terminate at shallow burrows (Fig. 5B), and continue on the reverse side of the bed (Fig. 5C). Similar epichnial grooves associated with circular depressions have been described as "annelid trails" by Hall (1852:pl. 14, fig. 3). These forms have subsequently been assigned to *A. fossulata* by Buckman (1994). If Hall's specimens from the Silurian of New York are truly conichnogeneric with the Deadwood forms of *Archaeonassa*, then both represent the only recorded specimens exhibiting this particular behavior in the ichnogenus. All previously recorded occurrences of *Archaeonassa* were collected from intertidal deposits (Buckman, 1992,

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Fig. 4.—Cross section from the Little Elk Creek section in the east to the Bridal Veil Falls section in the west, illustrating vertical and lateral distribution of Deadwood Formation and Aladdin Sandstone paleoenvironments, along with corresponding Seilacherian, marine soft-ground ichnofacies. Horizontal line ("T") represents hypothetical time line used in Figure 16.

Table 1.—*Summary of major lithofacies, associated trace fossils, and interpreted environments of deposition of the Deadwood Formation and Aladdin Sandstone. Under the column headed by "Trace Fossil Assemblages," D. T. = Dominant Trace, and S. T. = Subordinate Trace. Ethological interpretations of trace fossils from Frey and Pemberton (1984, 1985).*

| Lithofacies | Lithology | Primary sedimentary structures | Trace fossil assemblage | Environment of deposition |
|---|---|---|---|---|
| Lithofacies 1: Irregularly bedded hematitic sandstone. | Dolomitic–calcareous, ferrugenous, fine- to medium-grained sandstone, with minor shale partings. | Multidirectional ripples<br>Herringbone crossbedding<br>Hummocky bedding<br>Minor flaser bedding<br>Mudcracks | D. T.: Fodinichnion of *Planolites.*<br>S. T.: Fodinichnion of ?*Teichichnus* and *Trichophycus.*<br>Domichnion of *Skolithos* and *Palaeophycus.*<br>Repichnion of *Archaeonassa.* | Inner sand flat<br>Low energy, variable salinity, subaerial exposure |
| Lithofacies 2: Interbedded sandstone and siltstone. | Calcareous, glauconitic, fine-grained sandstone.<br>Calcareous, glauconitic siltstone, with thin shale partings.<br>Finely crystalline, argillaceous limestone. | Flaser-wavy bedding<br>Multidirectional ripplemarks<br>Herringbone crossbedding<br>Parting lineations<br>Mudcracks | D. T.: Repichnion of *Archaeonassa* and *Scolicia.*<br>Domichnion of *Palaeophycus, Skolithos,* and *Arthraria.*<br>Fodinichnion of *Gyrolithes* and *Planolites.*<br>S. T.: Cubichnion of *Rusophycus.*<br>*Repichnion of Cruziana* and "Ribbed Trail."<br>Fodinichnion of ?*Teichichnus,* ?*Arthrophycus, Trichophycus, Psammichnites,* and "Branched Burrow." | Outer sand flats<br>Moderate energy, high energy near low-tide line, subaerial exposure |
| Lithofacies 3: Interbedded shale and intraclastic limestone. | Multicolored, calcareous, fissile shale.<br>Dark gray, finely crystalline limestones.<br>Lenticular intraclastic limestones. | Strong fissility of shale<br>Chaotic orientation of intraclasts<br>Hardground development | D. T.: Cubichnion of *Rusophycus.*<br>Repichnion of *Cruziana* and *Didymaulichnus.*<br>Fodinichnion of *Psammichnites* and *Crossopodia.*<br>S. T.: Repichnion of *Archaeonassa.*<br>Fodinichnion of *Thalassinoides, Planolites, Taenidium,* and "Gently Curved Trace." | Restricted subtidal shelf<br>Slow sedimentation with periodic tempestite deposition |

Table 1.—*Continued.*

| Lithofacies | Lithology | Primary sedimentary structures | Trace fossil assemblage | Environment of deposition |
|---|---|---|---|---|
| Lithofacies 4: Crossbedded sandstone. | Medium- to coarse-grained calcareous sandstones.<br>Thick to massive, coarse-grained hematitic, dolomitic sandstones.<br>Metaquartzite conglomerate at base of facies. | Large-scale trough crossbeds<br>Large-scale tabular crossbeds<br>Parting lineations | D. T.: Domichnion of *Skolithos.*<br>S. T.: Fodinichnion of ?*Planolites.* | High energy beach<br>Shifting substrate, well aerated |
| Lithofacies 5: Hematitic sandy limestone. | Very argillaceous, sandy, hematitic fine- to medium-crystalline limestone, and dolomitic limestone. | Wavy bedding<br>Laterally discontinuous<br>Associated with lithofacies 1 and 2 | No trace fossils found. | Carbonate flat? |


Fig. 5.—A–C. *Archaeonassa fossulata* Fenton and Fenton. A. Note pronounced lateral ridges bounding smooth medial groove, KSU 4597, concave epirelief, lithofacies 2, Little Elk Creek section. B. KSU 4556; note that trail terminates at a shallow burrow, concave epirelief, lithofacies 2, Deadwood type section. C. Reverse side of KSU 4556 illustrating exit trail, convex hyporelief. D, E. *Arthraria antiquata* Billings, both specimens figured occur in convex hyporelief from lithofacies 2, Bridal Veil Falls section. D. KSU 4539. E. KSU 4548. F. ?*Arthrophycus* ichnospecies, KSU 4590, lithofacies 2, Little Elk Creek section. Bar scales in Fig. A–C and D represent 1 cm; bar scales in Fig. E and F represent 5 mm.

1994). All but two of the Deadwood specimens of *A. fossulata* were collected from lithofacies 1 and 2, which are interpreted as forming under intertidal conditions. This suggests that *Archaeonassa* may be an indicator of these environments.

*Facies.*—At the Deadwood type locality: KSU 4556 was collected at the top, while other specimens were collected at 0.3, 2.7, 4.5, and 6.5 m above the base of lithofacies 2; one specimen was collected 3.5 m above the base and two specimens were collected 2.5 m above the base of lithofacies 1. At Little Elk Creek: KSU 4597 was collected 0.5 m above the base of lithofacies 2. At Bridal Veil Falls: two specimens were collected 1.8 m above the base of lithofacies 3.

Ichnogenus *Arthraria* Billings, 1872
*Arthraria antiquata* Billings, 1872
(Fig. 5D, E)

*Material Examined.*—All specimens were collected from the Bridal Veil Falls locality, which include reposited specimens KSU 4537, 4539, 4540, 4542, 4545, and 4548.

*Description.*—Small dumbell- to femur-shaped traces preserved in convex hyporelief; averaging 5–10 mm long, but can be up to 15 mm long; trace consists of two bulbous terminations of varying shape and size, connected by a shallow ridge; bulbous terminations range from 4–6 mm in diameter, and are usually 1–2 mm higher than the connecting ridge in transverse profile; shape of terminations vary on individuals; ranging from spherical, arrow-shaped to heart-shaped; surface of connecting ridge may have fine longitudinal striations; sectioning of trace revealed no vertical component to bulbous terminations or retrusive spreiten extending into bedding.

*Discussion.*—The absence of vertical shafts extending from the bulbous terminations, or retrusive or protrusive spreite between the terminations differentiates *Arthraria* from *Bifungites* and *Diplocraterion* (Fillion and Pickerill, 1984). In their taxonomic reevaluation of *Arthraria*, Fillion and Pickerill (1984) noted that all of their specimens from Bell Island were collected from shallow, intertidal to subtidal flat and lagoonal deposits. All of the Deadwood specimens were collected from lithofacies 2, which is interpreted as forming within the outer intertidal zone (Fig. 16; Table 1). This suggests that *Arthraria*, like *Archaeonassa*, may be used as an indicator of these environments of deposition.

*Facies.*—KSU 4542 and 4548 were collected 1.5 m above the base of lithofacies 2. The remaining specimens were collected at the base of lithofacies 2.

Ichnogenus *Arthrophycus* Hall, 1852
?*Arthrophycus* ichnospecies
(Fig. 5F)

*Material Examined.*—A single specimen (KSU 4590) was collected from the Little Elk Creek section. There were numerous specimens observed along the underside of large slabs at the Deadwood type section, but none were collectable.

*Description.*—Convex hyporelief, weakly bilobed burrow oriented horizontal to bedding; burrow diameter 15 mm, incomplete length of 39 mm; ornamentation consists of poorly developed, transverse annulations giving burrow surface a corregated appearance; annuli occur as six alternating shallow furrows and ridges, each averaging 5 mm wide in longitudinal direction. Internal structure of burrow consists of obliquely oriented retrusive spreite; spreite ranging from 2–5 mm thick, sloping at 20–30° to bottom of burrow. In transverse section burrow cross section quadrate; height, 12 mm above bedding; retrusive spreite oriented concave-up, appearing as staked gutters; composition of spreite consisting of a fine-grained clastic material texturally different than host matrix.

*Discussion.*—Because of the incompleteness of this burrow only a tentative assignment to *Arthrophycus* can be made. Typically, this ichnogenus exhibits branching morphology similar to *Phycodes* (Hall, 1952; Osgood, 1970; Häntzschel, 1975:W39, pl. 25, fig. 4). Similarities between this specimen and *Arthrophycus* include the quadrate profile, weak bilobed morphology, and corrugated appearance of the burrow surface. The bilobed morphology coupled with the delicate transverse annulations help distinguish *Arthrophycus* from *Phycodes*, and similar spreite-bearing ichnogenera like *Teichichnus* (Osgood, 1970). The orientation of the spreite in the burrow, combined with the infilling material being texturally different from the host rock indicates that *Arthrophycus* was actively infilled by the trace maker.

*Facies.*—The specimen was collected 4.5 m above the base of lithofacies 2. Specimens observed in the field were all from beds pertaining to lithofacies 2.

Ichnogenus *Crossopodia* M'Coy, 1851
*Crossopodia* ichnospecies
(Fig. 6A, B)

*Material Examined.*—Two specimens on a single slab (KSU 4542) and a single specimen (KSU 4544) were collected from the Bridal Veil Falls section.

*Description.*—Straight to gently curving, longer than wide, distinctly bilobed trace preserved in concave and convex epireliefs; trace width between 5–10 mm, not constant along full length of trace due to undulating lateral margins; lobes covered by coarse striae, grouped five to seven striae per centimeter, angled 20° to midline; striae represent external expression of backfill menisci, and give lateral margins a ropy texture and trace a feather-like appearance; composition of menisci same as host matrix; lobes separated by a 1–2 mm-thick median groove in convex epirelief forms, or ridge in concave epirelief forms; menisci do not extend into median area. In transverse section trace has low triangular profile where apex is flatly truncated by median groove.

*Discussion.*—The precise relationship between *Crossopodia* and other ichnogenera having similar morphologies needs examination. Several authors have suggested that *Crossopodia* is conichnogeneric with *Psammichnites* and even *Cruziana* (Eagar et al., 1985; Maples and Suttner, 1990). Unlike *Cruziana*, *Crossopodia* is a three-dimensional backfill trace, and although the concave epirelief specimens of *Crossopodia* superficially resemble *Cruziana* (Fig. 6A), they actually represent the epichnial groove of a washed-out, full-relief form. *Psammichnites* is also morphologically similar to *Crossopodia*. Particularly when *Psammichnites* is preserved as convex epireliefs (compare Fig. 6B with 11A). However, the presence of a distinct but unstriated medial groove in *Crossopodia*, rather than a medial lobe as in *Psammichnites*, separates the two ichnogenera. The menisci of *Crossopodia* represent backfill structures, and are morphologically similar to ?*Crossopodia* from the Pennsylvanian Fountain Formation of Colorado (Maples and Suttner, 1990). The ?*Crossopodia* from the Fountain Formation has backfill menisci consisting of oriented mica flakes. This differentiates it from our specimens from the Deadwood Formation, where the menisci do not represent any textural or mineralogical difference from the hosting matrix. *Crossopodia* exhibits two distinct morphological types that may reflect gross behavioral or morphological differences in the trace makers. *Crossopodia* specimens from the Cretaceous have menisci bundles that are coarsely lobate and oriented at a transverse to oblique angle from the midline (Hattin and Frey, 1969). This type was interpreted to have formed from a nekto–benthonic organism, which would briefly alight on the sediment–water interface in constructing the trace before swimming off. Other

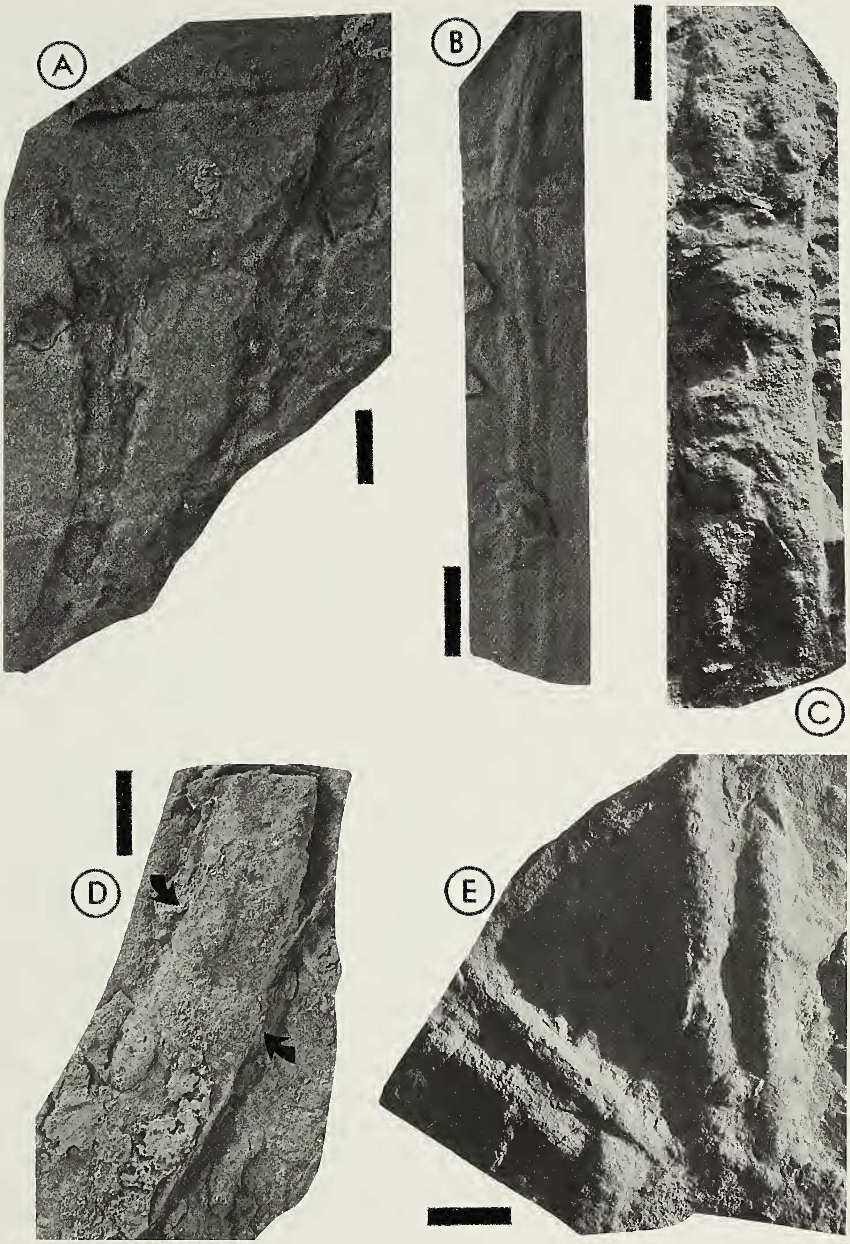



Fig. 6.—A, B. *Crossopodia* ichnospecies. A. KSU 4542, concave epirelief, lithofacies 2, Bridal Veil Falls section. B. KSU 4544, convex epirelief, lithofacies 3, Bridal Veil Falls section. C. *Cruziana* ichnospecies A, note distinct bilobed terminations that become poorly defined in middle of trace, also note coarse striations; KSU 4667, convex hyporelief, lithofacies 3, Little Elk Creek section. D. *Cruziana pudica* James, note faint *Rusophycus*-like swellings at arrows; KSU 4547, lithofacies 3, Bridal Veil Falls section. E. *Cruziana* ichnospecies B, KSU 4667, convex hyporelief, lithofacies 3, Little Elk Creek section. Bar scales represent 1 cm.

*Crossopodia*, such as specimens from the Upper Cambrian Deadwood Formation, the Pennsylvanian of Colorado (Maples and Suttner, 1990), the Upper Pennsylvanian of Kansas (Bandel, 1967), the Silurian of New York (Hall, 1852:pl. 13, fig. 1b), and the Ordovician of France (Häntzschel, 1975:pl. 34, fig. 2b), exhibit menisci bundles that are finer and oriented more acute to the midline of the trace. Most of these forms are interpreted to represent a more benthonic mode of life of the trace maker (Bandel, 1967). *Crossopodia* is restricted to the distal intertidal and subtidal lithofacies of the Deadwood Formation (Fig. 3, 10).

*Facies*.—KSU 4542 was collected 2 m above the base of lithofacies 2. KSU 4544 was collected 3.1 m above the base of lithofacies 3.

Ichnogenus *Cruziana* d'Orbigny, 1842
*Cruziana pudica* James, 1885
(Fig. 6D)

*Material Examined*.—Specimen KSU 4547 was collected at the Bridal Veil Falls location.

*Description*.—Longer than wide, weakly bilobed trace preserved in convex hyporelief; width variable, ranging from 12–14 mm, incomplete length 50 mm; height no more than 5 mm above bedding; trace composed of three individual *Rusophycus*-like swellings averaging 10 mm in length, and represent widest part of hypichnial ridge; swellings separated 20–40 mm in longitudinal direction by interlobate ridge; lobate swellings and interlobate areas divided medially by faint groove; groove 1–2 mm wide, and no more than 0.5 mm deep; lobe and interlobe surfaces ornamented with poorly preserved, oblique striae angled 60–70° from the midline, grouped five to six striae per centimeter; striae parallel to each other near midline, diverge and converge at lateral margins. In transverse section, trace cross section quadrate, with greatest height at *Rusophycus* swellings.

*Discussion*.—The assessment of this *Cruziana* to *C. pudica* is based on the ethological intergradation between *Cruziana* and *Rusophycus* observed in this ichnospecies (Osgood, 1970; Pickerill, 1977). The figured specimen shows an interconnected series of *Rusophycus*-like swellings (arrows in Fig. 6D), indicating that the trace maker vertically excavated into the substrate, then moved forward for a short distance before repeating the procedure. This intergradation in ethological types is seen in the Deadwood material and in specimens from the Ordovician of Ohio and Wales (Osgood, 1970; Pickerill, 1977). Other similarities between the Deadwood and Ordovician specimens are the presence of a weak median groove and poorly developed striated lobe surfaces. Because of the dual ethological nature exhibited in this ichnospecies, various authors have classified it as both *Rusophycus* (Hall, 1852; Osgood, 1970) and *Cruziana* (James, 1885; Seilacher, 1970; Pickerill, 1977). Because the predominant component of movement is lateral rather than vertical, we are inclined to agree with Pickerill's (1977) classification of the ichnospecies under *Cruziana*.

*Facies*.—This specimen was collected 1.5 m above the base of lithofacies 3.

*Cruziana* ichnospecies A
(Fig. 6C)

*Material Examined*.—A single specimen (KSU 4667) was collected on a large slab from the Little Elk Creek locality.

*Description*.—Poorly developed bilobed trace preserved in convex hyporelief; width 12 mm, length 65 mm, height 3 mm above bedding; lobes well developed at ends, become indistinct medially; where developed, lobes 5–6 mm wide, tapering to 3 mm wide at ends; covered with coarse striae that give trace a corrugated appearance; striae 1–1.5 mm thick, grouped three to four striae per centimeter, oriented at 60–70° from midline. In transverse section trace has semicircular cross section where lobes are well developed, becoming quadrate where individual lobes are ill defined.

*Discussion.*—Unlike typical *Cruziana*, this specimen does not show complete bilobed morphology along its entire length. This characteristic may have been due to postconstruction erosion that washed out the epichnial furrow, or represents a behavioral variation of *Cruziana*. Close examination of the specimen revealed no preservational irregularities or scouring. This observation was reinforced by the lack of abrasion or scouring of other traces on the same slab. Consequently, the weak bilobate morphology coupled with coarse, transversely directed striae probably represent a behavioral variate with the trilobite having a procline, or head-down attitude during trace construction (Seilacher, 1970:452, fig. 4).

*Facies.*—This specimen was collected 29 m above the base of lithofacies 3.

### *Cruziana* ichnospecies B
(Fig. 6E)

*Material Examined.*—Two specimens were collected on a single slab (KSU 4667) along with *Cruziana* ichnospecies A from the Little Elk Creek locality.

*Description.*—Longer than wide, distinctly bilobed trace preserved in convex hyporelief; width from 12–16 mm, length from 28–45 mm, height from 2–6 mm above bedding; lobes typically one-third total width of trace; 3–4 mm wide in small specimen, 6–8 mm wide in large specimen; lobes separated by distinct medial groove that is one-third total trace width, and 2 mm deep; groove expands at trace terminations forming distinct V-shaped gap between lobes, gap more prominent in smaller forms. Medially, lobes ornamented with very short, transversely oriented striae ranging from 0.5–2 mm thick, grouped eight to nine striae per centimeter; medial striae better developed in large forms. Laterally, lobes have fine, longitudinally-directed striations running parallel to trace margins; lateral striae better developed in smaller forms. In transverse section, trace has triangular cross section, while individual lobes are quadrate-shaped, with steep-sided lateral margins; highest part of trace at interior margin of lobes adjacent to median groove, with trace gently tapering to bedding anteroposteriorly and laterally.

*Discussion.*—The dual set of striae, with one on the exterior and the other on the interior parts of the lobes, is typical of Cambro–Ordovician *Cruziana* (Seilacher, 1970:449–452, fig. 3). The interior, oblique striae probably were constructed by movement of the trilobite endopodites that facilitated locomotion of the organism through the sediment. The longitudinal striae along the lobes' outer margins were likely produced by the expodites or gill structures being dragged as the animal moved forward.

*Facies.*—These specimens were collected 29 m above the base of lithofacies 3.

### *Cruziana* ichnospecies C
(Fig. 7A)

*Material Examined.*—A single specimen (KSU 4600) was collected from the Little Elk Creek section.

*Description.*—Longer than wide, strongly bilobed trace preserved in convex hyporelief; width 13 mm, length 30 mm, height 4 mm above bedding. Lobes approximately one-half total width, separated by a distinct, narrow median groove; groove 1.5 mm wide, 2–3 mm deep; lobes covered with fine and coarse striae; fine striae less than 0.5 mm thick, oriented at 70–75° from midline; coarse striae typically 1 mm thick, oriented at 25–45° from the midline; striations grouped at nine to 11 per centimeter; coarse striae typically cut fine striae. In transverse section lobes have semicircular cross section, with steep-sided lateral margins.

*Discussion.*—One feature of interest is that this trace appears to merge into a highly bioturbated region that resembles a poorly defined *Rusophycus*.

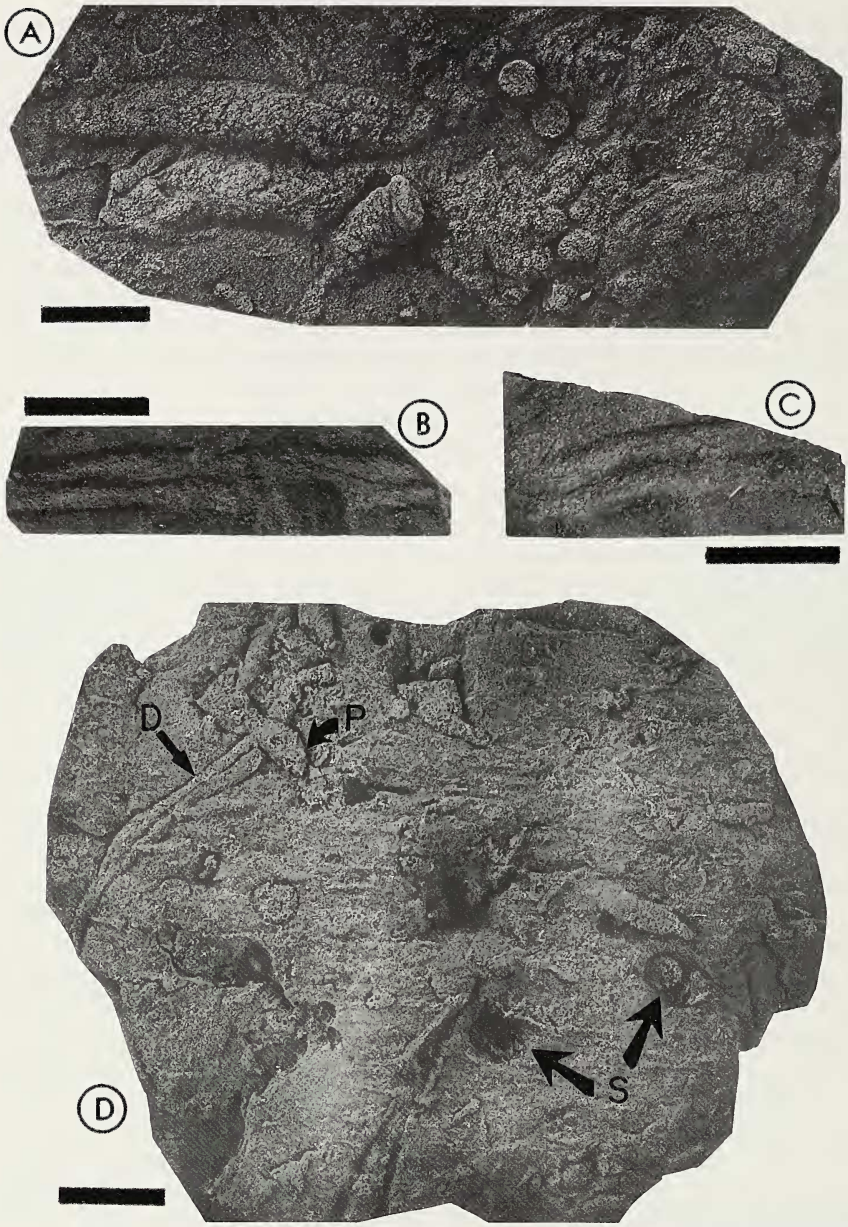



Fig. 7.—A. *Cruziana* ichnospecies C on left merging with a *Rusophycus*-like trace on right of figure, also note crosscutting of trace by ?*Planolites* burrows; KSU 4600, convex hyporelief, lithofacies 3, Little Elk Creek section. B–D. *Didymaulichnus lyelli* (Rouault). B, C. Both specimens occur on same slab; KSU 4525, convex hyporelief, lithofacies 3, Bridal Veil Falls section. D. Slab with *D. lyelli* (represented by letter "D"), note morphological shift from a bilobed hypichnia (top of trail) to a single ridge structure (bottom of trail); also on same slab are *Planolites beverleyensis* (represented by letter "P"), and *Skolithos* ichnospecies (represented by letter "S"); narrow striations and ridges oriented from left to right on slab represent parting lineations; KSU 4676, convex hyporelief, lithofacies 2, Deadwood type section. Bar scales represent 1 cm.

*Facies.*—This single specimen was collected 8 m above the base of lithofacies 3.

Ichnogenus *Didymaulichnus* Young, 1972
*Didymaulichnus lyelli* (Rouault, 1850)
(Fig. 7B–D)

*Material Examined.*—Two specimens occur on a single slab (KSU 4525) collected at the Bridal Veil Falls locality. A single specimen (KSU 4676) was collected at the Deadwood type locality.

*Description.*—Trace smooth, unornamented, bilobed over most of trace length, but may merge into single ridge structure, preserved in convex hyporelief; trace varies from 3–5 mm wide when bilobed, about half this width when occurring as a single ridge; length incomplete; lobes typically separated by narrow, well-developed median groove that is one-fifth total width of trace; groove about one-half as deep as lobes are high; lateral margins undulatory. In transverse section lobes have semicircular cross section.

*Discussion.*—The Deadwood forms of *D. lyelli* closely resemble, both in size and shape, specimens from the Ordovician of Portugal (Häntzschel, 1975:W61) and from the Upper Cretaceous Cardiff Formation of Alberta (Vossler et al., 1989). Particularly, all illustrated forms of *D. lyelli* exhibit transverse undulations along the lateral margins of the trace. Various trace makers and ethological interpretations have been suggested for *Didymaulichnus*, ranging from arthropods, gastropods, and worms (Glaessner, 1969; Young, 1972). On the basis of the morphological shift from a bilobed to single ridge repichnion (Fig. 7D), however, the Deadwood specimens probably represent locomotion of gastropods (Stanley, 1984; Vossler et al., 1989). For the purposes of this paper, *D. lyelli* is tentatively classified as a repichnion based on the unmeandering disposition of the ichnogenus and lack of evidence for active fill. Other than the occurrence of *D. lyelli* in the Cardiff Formation, which is interpreted as a normal marine shelf deposit, all other reported occurrences of the ichnospecies have been from marginal–marine to very nearshore deposits (Eager et al., 1985; Hakes, 1985). This may suggest that at least Early Paleozoic forms of this ichnospecies indicate these depositional regimes.

*Facies.*—KSU 4525 was collected 4.8 m above the base of lithofacies 3. KSU 4676 was collected 6.5 m above the base of lithofacies 2.

Ichnogenus *Gyrolithes* de Saporta, 1884
*Gyrolithes polonicus* Fedonkin, 1980
(Fig. 8A, B, D)

*Material Examined.*—Numerous specimens collected on two large slabs (KSU 4526, KSU 4530) at the Bridal Veil Falls locality.

*Description.*—Semicircular to semi-ovoid trace in plan view, with spiral vertical component in transverse view, preserved in full relief, concave hyporelief, or concave epirelief; epireliefs represent washed-out full-relief structures; diameter of trace ranges from 14–30 mm; concave epirelief forms (Fig. 8A) consisting of annulated U-shaped groove flanked by narrow lateral ridges; groove may be bisected by well-defined, narrow, median ridge; groove and median ridge ornamented with arcuate annulations; annuli average 1 mm thick, and are regularly spaced along trace length; full relief forms consist of structureless, infilled burrow with no ornamentation; infilling material appears same as host matrix; groove or full-relief burrow average 2.5–5 mm wide. In transverse section, trace corkscrews into host medium; vertical distance between each whirl varies from 3–5 mm.

*Discussion.*—Deadwood specimens of *G. polonicus* are similar in size and shape to those collected from the Lower Cambrian of Newfoundland (Crimes and

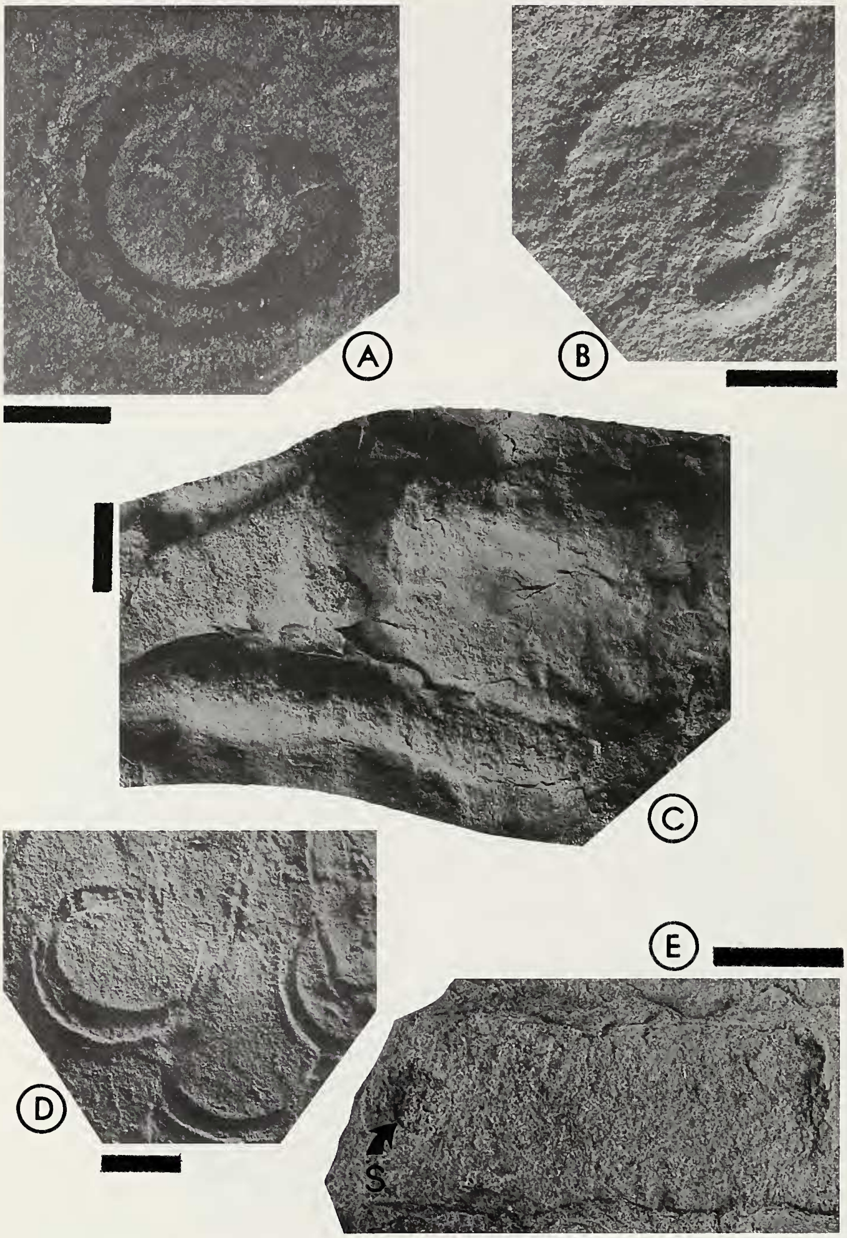



Fig. 8.—A, B, D. *Gyrolithes polonicus* Fedonkin. A. KSU 4530, illustrating median ridge and annulated trace margins, concave epirelief. B. Reverse side of KSU 4530, thickness of bed separating epichnial side from hypichnial side is 5 mm; concave hyporelief, lithofacies 2, Bridal Veil Falls section. D. Concave hyporelief cast of full-relief burrow; note faint annulations on burrow floor in specimen on left; KSU 4526B, lithofacies 2, Bridal Veil Falls section. C. *Palaeophycus alternatus* Pemberton and Frey, KSU 4546; convex hyporelief, lithofacies 2, Deadwood type section. E. *Palaeophycus crenulatus* Buckman, note burrow is crosscut by a *Skolithos* (labeled by letter "S"); KSU 4557, convex hyporelief, lithofacies 2, Deadwood type section. Bar scales represent 1 cm.

Anderson, 1985) and the Onega Platform of eastern Europe (Fedonkin, 1977). Typically this ichnospecies is characterized by a structureless, full-relief burrow that has a vertical, corkscrew behavior. However, some Deadwood forms of *G. polonicus* are unique in that the internal features of the burrow are evident (Fig. 8A, D), consisting of an annulated epichnial groove with a median ridge. The annulated interior of the burrow suggests a trace maker using peristaltic movement to construct the trace. Examination of the specimens preserved in full relief show that the infilled sediment is the same as the host material, suggesting the burrows were passively filled. *Gyrolithes polonicus* probably represents a fodinichnion, based on the elaborate geometry of the trace. As with *Arthraria antiquata* and *Archaeonassa fossulata*, *G. polonicus* appears to be restricted to the outer sand-flat facies (lithofacies 2), and could be an indicator of these environments of deposition (Fig. 16).

*Facies.*—All specimens were collected in the basal 1 m of lithofacies 2.

Ichnogenus *Palaeophycus* Hall, 1847
*Palaeophycus alternatus* Pemberton and Frey, 1982
(Fig. 8C)

*Material Examined.*—Two specimens on a single slab (KSU 4546) were collected at the Deadwood type section.

*Description.*—Straight to slightly curving burrow, oriented parallel to bedding, preserved in convex hyporelief or full relief; burrow diameters vary between 7–11 mm, not constant along burrow length; maximum burrow length is 80 mm; burrow thinly lined with fine-grained material similar to laminae of the host matrix; no collapse structures evident, but infilling material same as host material; burrow surface ornamented with alternating fine longitudinal striae and thick transverse annuli; striae thread-like, discontinuous but parallel to lateral margins of burrow; annuli occur as swellings along burrow wall, range 3–4 mm thick in longitudinal direction, average three to four annuli per centimeter; striae indistinct on annuli. In transverse section burrows extend 1–4 cm below bedding surface; burrow cross section ovoid to circular-shaped; oval burrows have long dimension parallel to bedding; no external or internal distortion of bedding laminae evident; upper contact of burrow with host matrix may be gradational.

*Discussion.*—The Deadwood specimens of *Palaeophycus alternatus* conform well to Pemberton and Frey's (1982) description. Typical of this ichnospecies is the alternating annulate and striate nature of the burrow wall, and general lack of internal collapse structure as noted in other ichnospecies of *Palaeophycus* (Pemberton and Frey, 1982; Buckman, 1995). However, in one specimen (burrow at top in Fig. 8C), the burrow shifts from a cylindrical to oval cross section along its length, which may indicate slight burrow collapse.

*Facies.*—*Palaeophycus alternatus* was collected 5 m above the base of lithofacies 2.

*Palaeophycus crenulatus* Buckman, 1995
(Fig. 8E)

*Material Examined.*—A single specimen (KSU 4557) was collected at the Deadwood type section.

*Description.*—Straight burrow preserved as convex hyporelief; diameter averages 15 mm; incomplete length of 35 mm; burrow distinctly lined with a fine-grained sand similar to host matrix; burrow lining with numerous, regularly spaced, transverse annuli; annuli range from 1–2 mm thick, average five annuli per centimeter. In transverse section burrow extends 4–6 cm below bedding surface; cross section oval, with long axis of ellipse parallel to bedding; collapse structure represented as concave-up laminae; internal composition of fill same as host matrix.

*Discussion.*—In his re-evaluation of *Palaeophycus*, Buckman (1995) noted that all annulated forms of *Palaeophycus* should be assigned to a new ichnospecies *P. crenulatus*, or to *P. alternatus*. This specimen from the Deadwood Formation conforms well with Buckman's (1995) description in that it has a distinct annulated lining but does not possess the longitudinal striations characteristic of *P. alternatus*. Differences between Buckman's (1995) figured specimens and our specimen do exist, however. *Palaeophycus crenulatus* from the Pennsylvanian Mullaghmore Sandstone of Ireland (Buckman, 1995:fig. 2A–D) exhibit finer annulations along the burrow wall that average one-half to one annulus per millimeter. The Deadwood specimen averages one annulus every two millimeters, with adjacent annuli being further apart. This variability in annulation does not warrant exclusion of the Deadwood burrow from *P. crenulatus*, and is probably due to the Deadwood form not having as tightly packed annuli as the European varieties. Other than the Carboniferous of Ireland (Buckman, 1995), *P. crenulatus* has only been recorded from the Jurassic of Greenland (Dam, 1990). This makes the Deadwood specimen the oldest assigned to this ichnospecies, and the only one reported from North America.

*Facies.*—This specimen was collected 3.5 m above the base of lithofacies 2.

*Palaeophycus sulcatus* (Miller and Dyer, 1878)
(Fig. 9A)

*Material Examined.*—Two specimens occur on a single slab (KSU 4586) collected at the Deadwood type locality.

*Description.*—Straight to gently curved burrow, oriented parallel to bedding, preserved in convex hyporelief; burrow diameters vary from 2–8 mm, remaining constant along burrow length; maximum length 50 mm. Burrow lining consisting of silt- to clay-sized material; sculptured with thin, irregular, longitudinal ridge and groove structures that give lining an anastomosing texture; ridges and grooves average 0.5 mm thick and range between 2–18 mm long. In transverse section, burrow cross section circular; height 0.5–5 mm above bedding; infilling material same as host matrix, with no collapse structure evident.

*Discussion.*—*Palaeophycus sulcatus* is differentiated from *P. alternatus* by the coarser striae and absence of annulations or swellings along the burrow wall (Pemberton and Frey, 1982; Buckman, 1995).

*Facies.*—Specimens were collected 5 m above the base of lithofacies 2.

*Palaeophycus tubularis* Hall, 1847
(Fig. 10A–C)

*Material Examined.*—*Palaeophycus tubularis* was identified in the field at all sections, most specimens occur on large slabs. Reposited material includes KSU 4566 and 4567 from the type locality.

*Description.*—Straight to gently curved, smooth, unornamented, thinly lined burrows preserved as convex hyporelief or full relief. Burrow diameters range from 3–20 mm, remaining constant along burrow length; lining consists of very fine-grained silt- or clay-sized material similar to shale partings of host bed. In transverse section burrow circular to oval in cross section; collapse structures and deformation laminae common in burrow interior; composition of fill same as host matrix; burrows occasionally exhibit gradational upper contacts with host bed.

*Discussion.*—*Palaeophycus tubularis* was collected from most of the Deadwood–Aladdin lithofacies, with the exception of lithofacies 3. Typical *P. tubularis* from lithofacies 1, which represents an environmentally stressful intertidal regime,

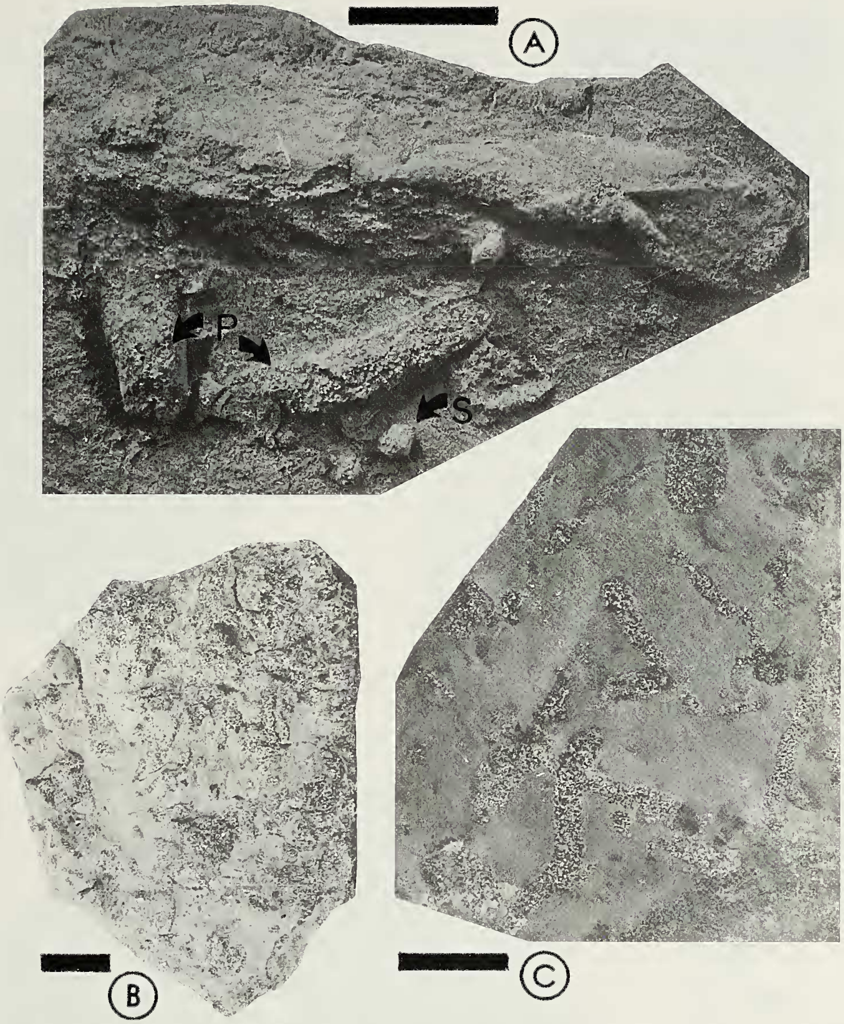



Fig. 9.—A. *Palaeophycus sulcatus* (Miller and Dyer), note association with *Planolites beverleyensis* (Billings) (represented by the letter "P") and *Skolithos* ichnospecies preserved as knob-like fillings of the burrows (represented by the letter "S"); full relief and convex hyporelief, lithofacies 2, Deadwood type section. B, C. *Planolites montanus* Richter, both figures preserved in full relief, collected from lithofacies 2, Deadwood type section, note textural and chromatic differences between traces and host lithology indicating active fill of burrows. B. KSU 4577. C. KSU 4579. Bar scales represent 1 cm.

were in the size range of 3–10 mm in diameter, having an average diameter of 7 mm. Collected specimens of *P. tubularis* from lithofacies 2, which represents a more normal marine intertidal setting, fell in the size range of 12–20 mm, with an average burrow diameter of 15 mm. Given the stressful conditions of the inner sand flats, such as variable salinity and oxygen, there may be an ecological cause to the disparity in size of *P. tubularis*. Similar characteristics have been observed in intertidal mollusks from the Gulf of California (Fürsich and Flessa, 1987), and in Pennsylvanian marginal marine trace-fossil assemblages of Kansas (Hakes, 1985).

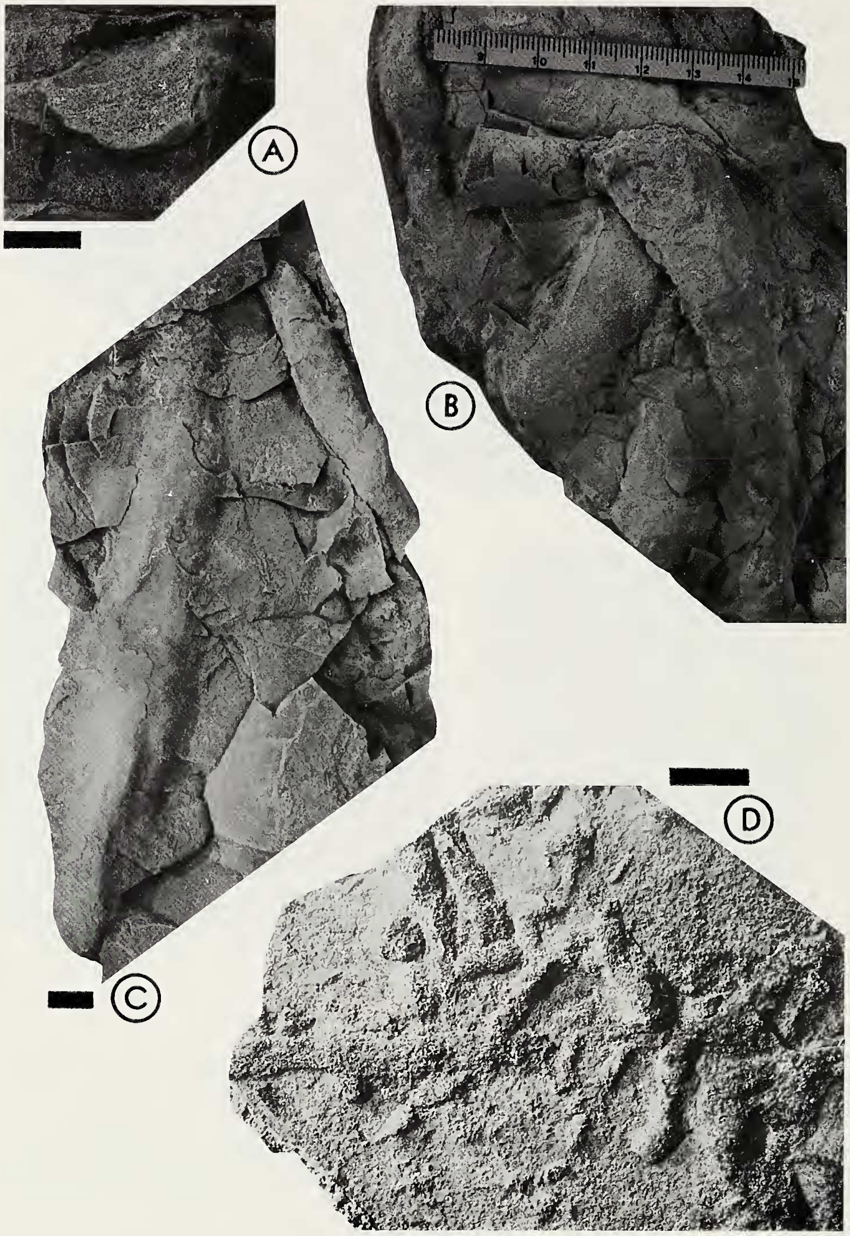



Fig. 10.—A–C. *Palaeophycus tubularis* Hall. A. Cross section of burrow figured in C, note concave-up laminae from collapsing of the burrow; KSU 4566, full relief, lithofacies 2, Deadwood type section. B. KSU 4567, full relief, lithofacies 2, Deadwood type section. C. Plan view of 9A, convex hyporelief to full relief, lithofacies 2, Deadwood type section. D. *Planolites beverleyensis* Billings, KSU 4523, full relief, lithofacies 2, Bridal Veil Falls section. Bar scales represent 1 cm.

*Facies.*—KSU 4566 and 4567 were collected 3.5 m above the base of lithofacies 2 at the type section. Other specimens from the type section were collected at 0.3, 5.0, and 6.5 m above the base of lithofacies 2, and at the base and 2.5 m above the base of lithofacies 1. At the Little Elk Creek section specimens were collected 4.5 m above the base of lithofacies 2 and 5.3 m above the base of lithofacies 1. At Bridal Veil Falls, specimens were collected at the base of lithofacies 2.

Ichnogenus *Planolites* Nicholson, 1873
*Planolites beverleyensis* Billings, 1862
(Fig. 7D, 9A, 10D)

*Material Examined.*—Numerous examples occur on single slabs (KSU 4586, 4558) collected at the Deadwood type section. Slab KSU 4523 was collected at the Bridal Veil Falls locality. Many specimens were also observed in the field at all of the measured sections, but were not collected.

*Description.*—Cylindrical, usually gently curved, sometimes straight, unlined burrows preserved in full relief; burrow diameters range from 7–12 mm, average 10 mm, remaining constant along burrow length in individuals; branching not evident, interruptions and crossovers common. Burrow fill structureless, consisting of a coarser-grained material than host matrix; burrows usually stand out on bedding due to discoloration of fill material. In transverse section burrows have circular cross section, and are oriented at various angles to bedding.

*Discussion.*—Deadwood representatives of *Planolites beverleyensis* appear slightly smaller than Pemberton and Frey's (1982) material. They are, however, 5–8 mm larger than *P. montanus* from the Deadwood, and have a less contorted burrow attitude. Generally, *Planolites* was collected from all lithofacies types, although it was more commonly found in lithofacies 1 and 2. Specifically, *P. beverleyensis* appears to be restricted to lithofacies 2.

*Facies.*—KSU 4586 and 4548 were collected 5.0 and 5.9 m above the base of lithofacies 2, respectively. KSU 4523 was collected 1.5 m above the base of lithofacies 2.

*Planolites montanus* Richter, 1937
(Fig. 9B, C)

*Material Examined.*—Specimens of *Planolites montanus* were observed and collected from all sections and lithofacies types. Specifically, KSU 4565, 4577, 4579, 4588, 4559, and 4569 represent slabs with numerous burrows collected from the Deadwood type section; KSU 4589, 4666, 4596, and 4675 were collected from the Little Elk Creek section.

*Description.*—Small, cylindrical, strongly curved to contorted, unlined burrows preserved in full relief. Burrow diameters vary from 1–4 mm, averaging 2.6 mm; diameter remaining constant in individuals. Sparsely populated bedding surfaces usually have curving burrows; burrows crowded on bedding surfaces are contorted. No branching evident, crossovers and burrow interruptions common. Burrow fill structureless; always coarser grained and having a different color than host matrix. In transverse section burrows have circular cross section, rarely oval; oriented at various attitudes to bedding.

*Discussion.*—*Planolites montanus* was found in all lithofacies of the Deadwood, but occurs in abundance in lithofacies 1. In their treatment of Lower Ordovician intertidal deposits in Argentina, Mángano et al. (in press) noted an extreme segregation in the taxonomic components of the trace-fossil assemblages.

High intertidal deposits contain only *P. montanus*. Other than the occurrence of a few *Palaeophycus* and *Trichophycus* ichnospecies, the inner sand-flat environments of the Deadwood Formation were dominated by *Planolites montanus*. This may suggest that in tidal-dominated, Lower Paleozoic siliciclastic sequences, monoichnospecific occurrences of *P. montanus* can be used to recognize high intertidal flat deposits.

*Facies*.—At the type section: KSU 4565 and 4577 were collected 3.5 m above the base of lithofacies 1; KSU 4579 and 4588 were collected 2.5 m, and KSU 4559 and 4569 were collected 5.9 m above the base of lithofacies 2. At the Little Elk Creek section: KSU 4675 was collected 3.5 m above the base of lithofacies 1; KSU 4589 was collected 3 m, and KSU 4666 was collected 9 m above the base of lithofacies 3.

Ichnogenus *Psammichnites* Torrel, 1870
*Psammichnites* ichnospecies
(Fig. 11A, C)

*Material Examined*.—One specimen occurs on a small slab (KSU 4534), and two specimens occur on a large slab (KSU 4535) collected from the Bridal Veil Falls locality.

*Description*.—Meandering to gently curved, longer than wide trace preserved in convex epirelief and full relief; width 5–11 mm; length variable, maximum 30 cm. Full-relief trace consists of a median lobe, laterally bounded by two platforms ranging from 3–4 mm wide; median lobe may be collapsed along parts of trace forming a groove; platforms bounded at lateral margins by narrow ridge structures averaging 1 mm wide; platforms horizontal to bedding; ridge and platform covered with fine, transverse ribbing indicative of backfill lamellae, and does not extend into median lobe; backfill material similar to host matrix; individual lamellae 0.8 mm thick, grouped seven to eight lamellae per centimeter. Specimens in epirelief poorly preserved (Fig. 11A); consisting of a single broad median lobe, bounded along lateral margins by a thin inner groove and outer ridge; ridge and groove with irregularly spaced striations oriented oblique to the midline of trace. In transverse section, burrows have an oval cross section, with the long axis of ellipse parallel to bedding.

*Discussion*.—Morphological differentiation between *Psammichnites* and *Scolicia* is based on the presence of a single ridge that symmetrically divides the backfilled string into two parts in the former ichnogenus (D'Alessandro and Bromley, 1987). *Scolicia* typically has two or more sediment strings. Backfill structures in *Psammichnites* are generally loosely packed compared to *Scolicia*. In the Deadwood forms this symmetrical ridge is represented by a broad lobe that does not exhibit transverse ribbing, suggesting loose packing of sediment by the trace maker. In their examination of the trace fossils from the lower Cambrian Ratcliffe Brook Formation in eastern Canada, Hofmann and Patel (1989:144, fig. 4a) illustrate *Psammichnites gigas* that look similar to our specimens from the Deadwood Formation. *Psammichnites gigas* consists of a medial lobe bounded laterally by narrow ridges. Hofmann and Patel (1989) also noted a similarity between their specimen of *P. gigas* and specimens of *Subphyllochorda* ichnospecies from the Ratcliffe Brook Formation (Hofmann and Patel, 1989:fig. 2d, e) and *S. laevis* from the Cretaceous of the Carpathians of Poland (Ksiazkiewicz, 1970:290, 1977:134–135, pl. 16, fig. 1–3). However, the authors were tentative in their assessment of the Ratcliffe Brooks *Subphyllochorda* and thought it may be a preservational variate of *Psammichnites* or *Scolicia*. As a taxonomic note, *Subphyllochorda* has recently been synonymized as *Scolicia* by Uchman (1995), who considers *Subphyllochorda* as the hypichnial expression of *Scolicia* (see dis-

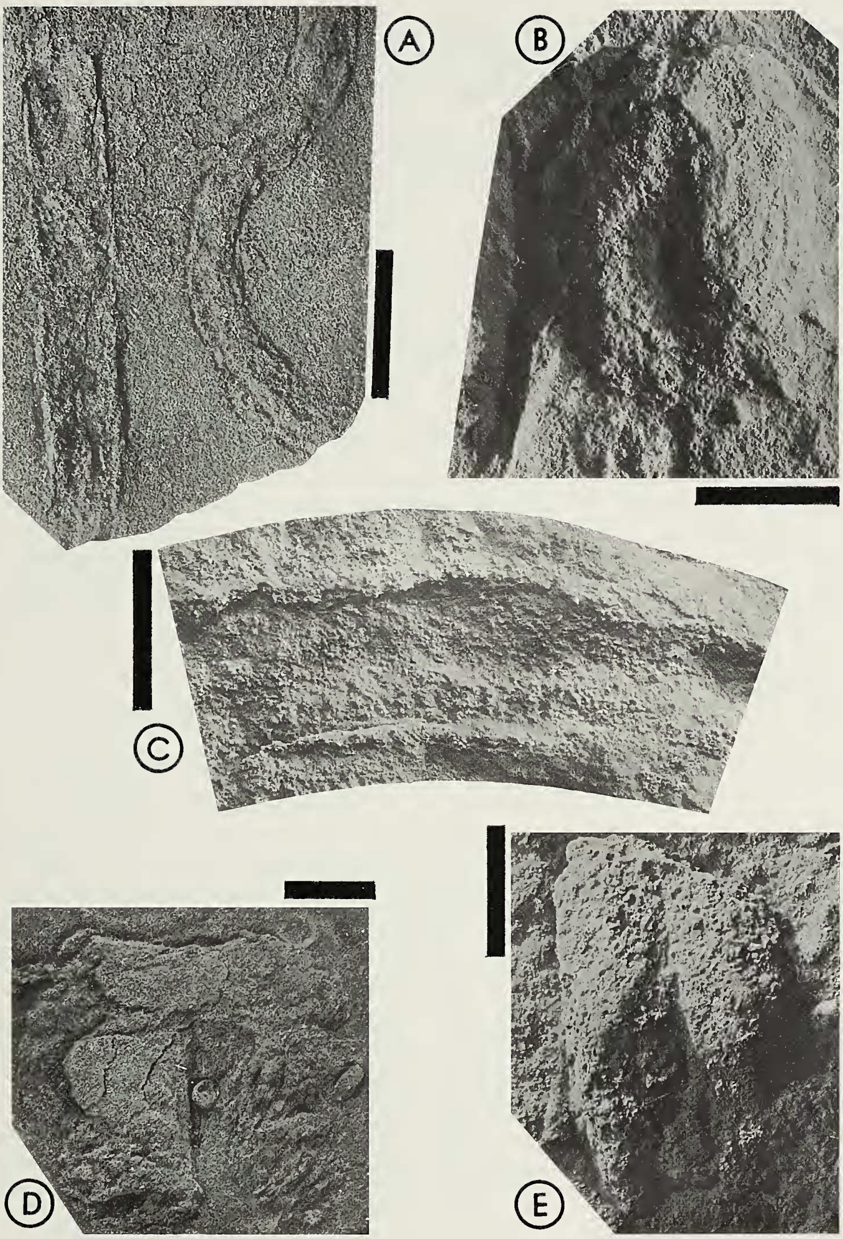



Fig. 11.—A, C. *Psammichnites* ichnospecies. A. KSU 4535, convex epirelief, lithofacies 2, Bridal Veil Falls section. C. KSU 4534, hyporelief counterpart, lithofacies 2, Bridal Veil Falls. B. *Rusophycus* cf. *R. dispar* Linnarsson, note genal and pygidial spine impressions of the trace maker preserved along the left and right posterior margins of the trace; KSU 4674, lithofacies 2, Little Elk Creek section. D. *Rusophycus latus* Webby, KSU 4598, convex hyporelief, lithofacies 3, Little Elk Creek section. E. *Rusophycus* cf. *R. pedroanus* Seilacher, KSU 4671, convex hyporelief, lithofacies 3, Little Elk Creek section. Bar scales represent 1 cm.

cussion under ?*Scolicia* in this section). The Deadwood specimens of *Psammichnites* appear to be morphologically distinct from *Scolicia* due to the lack of parallel sediment strings characteristic of that ichnogenus. The close similarity of the Deadwood *Psammichnites* with the material from the Ratcliffe Brooks Formation warrants assignment to *Psammichnites*; however, given the poor quality of the Deadwood specimens we are reluctant to categorize them as conichnospecific.

*Facies.*—KSU 4534 was collected 1.5 m above the base of lithofacies 2. KSU 4535 was collected 1 m above the base of lithofacies 2.

Ichnogenus *Rusophycus* Hall, 1852
*Rusophycus* cf. *R. dispar* Linnarsson, 1869
(Fig. 11B)

*Material Examined.*—A single specimen (KSU 4674) collected from the Little Elk Creek section.

*Description.*—Ovoid, mildly bilobed trace preserved in convex hyporelief; width 24 mm medially, tapering to 19 mm anteriorly and posteriorly; length 30 mm; lobes parallel, separated by shallow medial groove that expands to an oval-shaped gap in the middle of trace. Posteriorly, lobes covered with poorly developed, fine striae less than 1 mm thick, oriented at 40° to midline medially, curving to 25° from midline laterally; grouped six to seven striae per centimeter. Anteriorly, trace differentiated into a triangular-shaped region with indistinct striae. Left lateral margin of trace shows a distinct, 24 mm-long ridge that parallels trace margin; posterior margin shows five spine-like projections; projections widest at trace margin, tapering posteriorly; projections larger at the posterolateral margin, decreasing in size posteromedially. In transverse section, trace 5 mm high; highest part located medially, gradually tapering in lateral and anteroposterior directions.

*Discussion.*—Tentative designation to *R. dispar* is due to the lack of well-defined scratch marks in the anterior part of the burrow. In well-preserved specimens of *R. dispar*, anterior striae are directed posterolaterially from the midline (Fillion and Pickerill, 1990). Similarities with *R. dispar* from the ?Cambro–Ordovician of Newfoundland include the cubichnion's oval shape, the pronounced medial gap, and the acute angle the posterior striae make with the midline (Fillion and Pickerill, 1990:54, pl. 14, fig. 1). This form is unique in that impressions of the genal and pygidial spines of the presumed trilobite trace maker are preserved. Based on the triangular-shaped anterior margin, the long genal spine impression extending parallel to the lateral margin, and pygidial spine impressions that become larger at the posterolateral margin, the trace may have been constructed by dikelocephalid trilobites, which are similar in gross size and shape to this specimen. Faunal lists given in Kulik (1965) show that dikelocephalids are common at the base of the stratigraphic interval from which this specimen was collected.

*Facies.*—The specimen was collected 4.5 m above the base of lithofacies 2.

*Rusophycus latus* Webby, 1983
(Fig. 11D)

*Material Examined.*—A single specimen (KSU 4598) was collected at the Little Elk Creek locality.

*Description.*—Quadrate, bilobed trace preserved in convex hyporelief; width from 36 mm anteriorly to 30 mm posteriorly; length 32 mm; lobes parallel and distinct posteriorly, separated by 4.5 mm-wide median groove. Anteriorly, lobes merge to form a single platform that is approximately one-third the length of trace; platform ornamented with very coarse, transversely oriented striae; anterior striae having a more convergent–divergent pattern than posterior striae. Posterior bilobate section ornamented with coarse, 0.5–1 mm-thick, parallel striae, oriented at 40° to the midline, numbering eight to 12 striae per lobe; striae finer medially, coarsening laterally. In transverse section: trace shallow, extending no more than 4 mm above bedding; highest part along medioanterior margin, gently tapering laterally and posteriorly.

*Discussion.*—Seilacher (1970) classified both *Rusophycus*- and *Cruziana*-type traces of presumed trilobite origins under one ichnogenus, *Cruziana*, primarily as a matter of convenience because the two ethological types commonly intergrade. Webby (1982), in an examination of Lower Ordovician trace fossils from New South Wales, found no intergradations between *Cruziana* (furrowing trace) and Seilacher's *C. omanica* (resting type). As a consequence, Webby designated a new ichnospecies, *Rusophycus latus*, as complimentary cubichnia of *C. omanica*. Other reported occurrences of *R. latus* include the Lower Cambrian of California (Alpert, 1976) and Newfoundland (Crimes and Anderson, 1985; Narbonne et al., 1987), ?Cambro–Ordovician formations in Newfoundland (Fillion and Pickerill, 1990), and the Cambro–Ordovician units from Argentina (Mángano et al., in press). Similarities between all these specimens include the overall quadrate shape with a length–width ratio of $<1$, differentiation in the orientation and thickness of anterior versus posterior striations, lack of grouping of striae into distinct bundles, and the coarseness of the striae.

*Facies.*—This specimen was collected 8 m above the base of lithofacies 3.

*Rusophycus* cf. *R. pedroanus* (Seilacher, 1970)
(Fig. 11E)

*Material Examined.*—Three specimens occur on a single slab (KSU 4671) collected from the Little Elk Creek locality. A single specimen (KSU 4542) was collected at Bridal Veil Falls.

*Description.*—Longer than wide, bilobed trace preserved in convex hyporelief; width 15 mm, length from 25–30 mm. Individual lobes vary from 7 mm wide anteriorly to 4 mm wide posteriorly; lobes diverge posteriorly, becoming separated by prominent V-shaped median groove that varies from 1–5 mm going from anterior to posterior; surface ornamentation indistinct except for poorly developed, coarse striae on one specimen; striae from 1–2 mm thick; vary from 40–60° to the midline medially, to 70–80° from midline laterally. In transverse section trace shallow, extending 4–6 mm above bedding; lobes steep-sided and broadly semicircular in cross section.

*Discussion.*—The poor quality of the Deadwood specimens does not allow a definitive assignment to an ichnospecies. Based on the overall shape of the cubichnion, which consists of divergent lobes separated by a distinct V-shaped gap, our specimens resemble *R. pedroanus* from the Upper Silurian of Spain and Libya (Seilacher, 1970:fig. 7.25), and *R.* cf. *pedroanus* described from the ?Cambro–Ordovician of Newfoundland (Fillion and Pickerill, 1990:56, pl. 15, fig. 5). Other distinguishing characteristics are the very coarse striations on one of our specimens, which was described by Fillion and Pickerill (1990:56) as giving the trace a "corrugated appearance."

*Facies.*—KSU 4671 was collected 29 m above the base of lithofacies 3. KSU 4542 was collected 1.5 m above the base of lithofacies 2.

?*Rusophycus* ichnospecies
(Fig. 12C)

*Material Examined.*—A single specimen (KSU 4669) was collected as float at the Little Elk Creek locality.

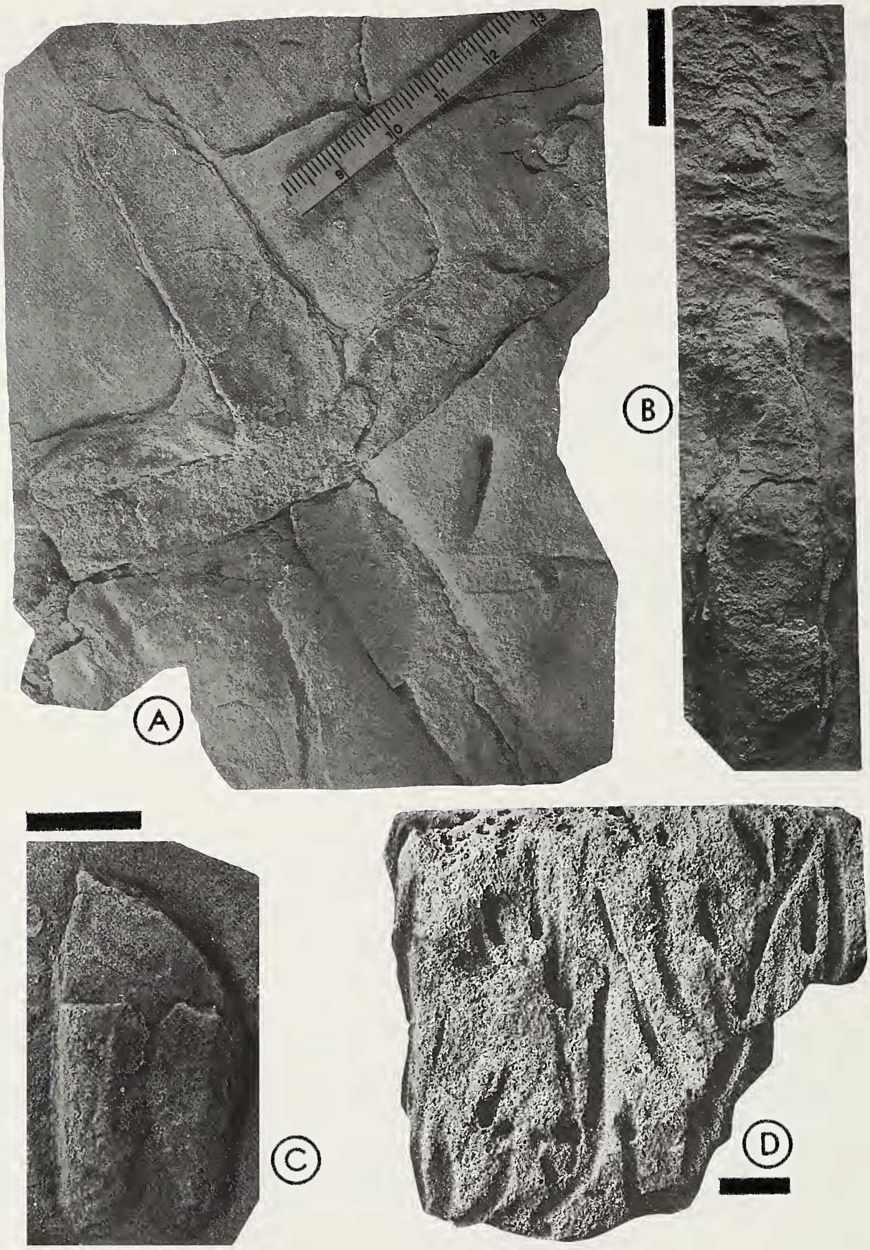



Fig. 12.—A, B. ?*Scolicia* ichnospecies. A. KSU 4590, concave epirelief, lithofacies 2, Little Elk Creek section. B. Note arcuate ridges leading to distinct hypichnial ridge; KSU 4681, convex hyporelief, lithofacies 2, Deadwood type section. C. ?*Rusophycus* ichnospecies, KSU 4669, convex hyporelief, lithofacies 3, Little Elk Creek section. D. *Skolithos* ichnospecies, typical form found in upper 2 m of the Aladdin Sandstone; KSU 4677, Deadwood type section. Bar scales represent 1 cm.

*Description.*—Bilobed trace preserved in convex hyporelief; width 17 mm, tapering to 15 mm at posterior(?) end; incomplete length. Lobes parallel, approximately one-half total trace width; separated by shallow medial groove that varies between 2–3 mm wide; groove distinct posteriorly(?), indistinct anteriorly(?). No surface striae evident. In transverse section trace extends 5 mm above bedding; lobes quadrate in cross section, flat crested, and form a steep angle to bedding surface.

*Discussion.*—Because this specimen is incomplete and poorly preserved, it is uncertain whether it represents a true *Rusophycus* or a broken *Cruziana.*

*Facies.*—Although collected as float, the slab on which this specimen is preserved is similar to the thin, lenticular siltstone beds described from lithofacies 3.

Ichnogenus *Scolicia* De Quatrefages, 1849
?*Scolicia* ichnospecies
(Fig. 12A, B)

*Material Examined.*—Two specimens on a single slab (KSU 4590) and another specimen (KSU 4681) were collected from the Little Elk Creek locality. Specimens KSU 4557 and 4572 were collected from the Deadwood type locality.

*Description.*—Single, large, deep furrow that may become weakly bilobed along its length; preserved in concave epirelief or convex hyporelief; width varies from 10–17 mm, averages 14 mm, remaining constant along trace length within individuals; length variable, maximum measured at 175 mm; furrow floor smooth (KSU 4590; Fig. 12A), composed of a finer-grained material than host matrix that may represent a lining. KSU 4681 (Fig. 12B) represents a single hypichnial ridge that becomes weakly bilobed at terminations; surface of furrow ornamented with fine, arcuate to straight transverse ridges that do not extend to trace margins; ridges grouped five to seven per centimeter. In transverse section epichnial furrow and hypichnial ridge has a quadrate cross section; depth or height of main structure ranges from 5–7 mm.

*Discussion.*—These specimens were originally assigned to *Palaeobullia* Götzinger and Becker based on similar morphology and mode of preservation with Pennsylvanian forms from Tennessee (Miller and Knox, 1985), and because of similarities with modern gastropod epichnia (Knox and Miller, 1985). Uchman (1995) has subsequently synonymized *Palaeobullia*, *Taphrhelminthopsis*, and *Subphyllochordia* into *Scolicia*. Most of these other forms, particularly *Palaeobullia* and *Taphrhelminthopsis*, represent preservational variates of washed-out *Scolicia*. Two of the Deadwood specimens do have the appearance of postconstruction erosion similar to that illustrated by Uchman (1995:text-fig. 2A, B; Fig. 12A). Uchman (1995) also suggests that similar washed-out traces (*Scolicia strozzii*) are possible preservational variates of *Curvolithus* or *Cruziana*. Neither *Curvolithus* nor *Cruziana* appear to be good candidates for the Deadwood specimens in that they represent a single hypichnial ridge or epichnial groove that is sometimes preceded by arcuate transverse ribs representing backfilling of the burrow (top half of Fig. 12B). The specimen in Figure 12D superficially resembles *Beaconites* illustrated in Häntzschel (1975:pl. 28, fig. 1). *Beaconites*, however, is characterized by a distinct wall enclosing the backfill menisci (D'Alessandro and Bromley, 1987; Keighley and Pickerill, 1994). The Deadwood specimens do not exhibit a wall structure. All specimens from the Deadwood resemble in gross morphology epichnial or hypichnial expressions of washed-out *Scolicia* with poorly developed sediment strings along the bottom of the burrow. The lack of bilobate or trilobate morphology of the Deadwood traces is the reason only tentative assignment to *Scolicia* is made.

*Facies.*—KSU 4557 and 4572 were collected 3.5 m above the base of lithofacies 2. KSU 4590 and 4681 were collected 4.5 m above the base of lithofacies 2.

Ichnogenus *Skolithos* Haldeman, 1840
*Skolithos* ichnospecies
(Fig. 7D, 8E, 12D)

*Material Examined.*—Specimens were collected from all localities and from most lithofacies except for lithofacies 3. Abundant *Skolithos* burrows are the most distinct feature of the upper 2 m of the Aladdin Sandstone.

*Description.*—Specimens on a large block (KSU 4677; Fig. 12D) are narrow, unbranched, vertical to slightly inclined shafts preserved in full relief; shafts vary between 1–2 mm in diameter, remaining constant in individuals; normally straight, but may curve slightly at distal portions of tube; length variable, maximum observed at 45 mm; walls unornamented. Specimens on slabs KSU 4586 and 4676 (Fig. 7D, 8E) are narrow vertical shafts, having circular to oval cross sections; shafts preserved in convex or concave hyporelief, concave epirelief, or full relief; shaft diameters range from 3–8 mm, average 5 mm, length incomplete; tube usually filled with sediment creating raised pimples in hyporelief and shallow depression in epirelief.

*Discussion.*—Some of the collected specimens of *Skolithos* from the Aladdin Sandstone (KSU 4677; Fig. 12D) appear conichnospecific to *Skolithos verticalis* (Alpert, 1974). The other specimens of *Skolithos* (KSU 4586 and 4676; Fig. 7D, 8E) are incomplete, but judging by their cross-sectional dimensions, may belong to *S. linearis* (Alpert, 1974). *Skolithos* is common throughout the outer sand-flat lithofacies (lithofacies 2) and off-shore parts of the inner sand-flat lithofacies (lithofacies 1). It is the most diagnostic feature of the upper 2 m of the Aladdin Formation, making the Aladdin one of the most easily recognizable and mappable formations in the Black Hills.

*Facies.*—Specimens collected and described from the Aladdin Sandstone (KSU 4677) occur within lithofacies 4 and represent a high-energy beach or barrier island complex. Other collected specimens usually occur in groups of ten or more individuals on a single slab and include KSU 4586 and 4676, collected 5 and 6.5 m, respectively, above the base of lithofacies 2 at the type section. At the Little Elk Creek section: KSU 4679 and 4681 were collected 3.3 and 4.5 m, respectively, above the base of lithofacies 2; KSU 4682 was collected 5.3 m above the base of lithofacies 1.

Ichnogenus *Taenidium* Heer, 1877
*Taenidium serpentinum* Heer, 1877
(Fig. 13A)

*Material Examined.*—Two specimens occur on a single slab (KSU 4544) collected from the Bridal Veil Falls locality.

*Description.*—Narrow, unlined, linear trace preserved in convex hyporelief; width 2 mm, maximum length 126 mm; trace margins slightly annulated; trace interior with numerous, regularly spaced, fine, transverse arcuate menisci that represent backfilling of burrow; menisci average 1.6 mm thick in longitudinal direction; grouped 16 menisci per centimeter. In transverse section burrow has semicircular to quadrate cross section; height no more than 2 mm above bedding.

*Discussion.*—The presence of evenly spaced, gently arcuate menisci that are about as thick as the burrow is wide, and lack of a wall support assignment of these specimens to *Taenidium serpentinum* (D'Alessandro and Bromley, 1987; Keighley and Pickerill, 1994).

*Facies.*—The specimens were collected 4.8 m above the base of lithofacies 3.

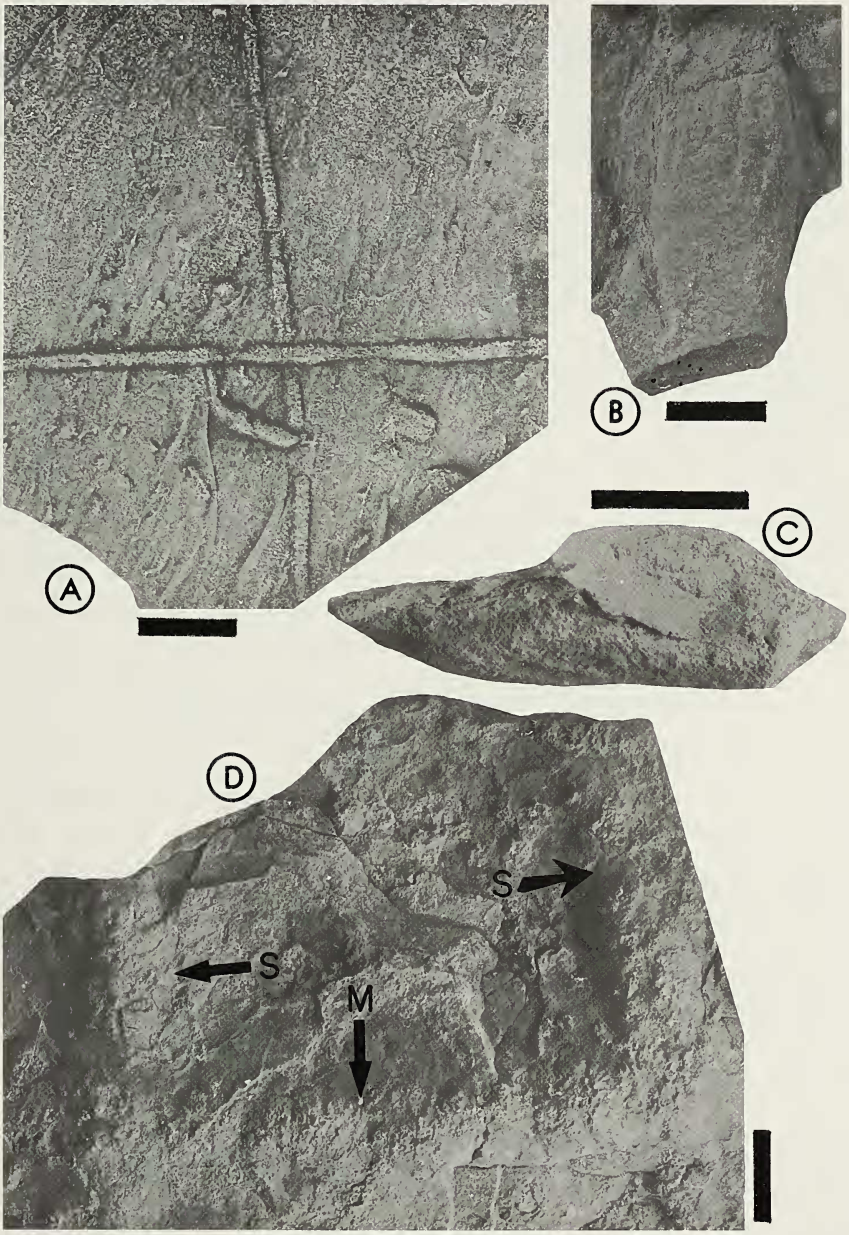



Fig. 13.—A. *Taenidium serpentinum* Heer, KSU 4544, convex hyporelief, lithofacies 3, Bridal Veil Falls section. B, C. ?*Teichichnus* ichnospecies. B. Full-relief partial burrow intersecting bedding on the left of figure; KSU 4574, lithofacies 2, Deadwood type section. C. Same specimen in transverse profile, note poorly preserved spreite. D. *Thalassinoides* ichnospecies, main burrow labeled as "M," secondary branches labeled with an "S"; KSU 4589, full relief, lithofacies 3, Little Elk Creek section. Bar scales represent 1 cm.

Ichnogenus *Teichichnus* Seilacher, 1955
?*Teichichnus* ichnospecies
(Fig. 13B, C)

*Material Examined.*—Specimen KSU 4574 was collected at the Deadwood type section, KSU 4682 from the Little Elk Creek locality.

*Description.*—Cylindrical burrow oriented parallel to bedding, except at end where it gradually deflects into bedding, preserved in full relief; width 15 mm, remaining constant along burrow length; incomplete length of 55 mm; retrusive spreite arranged as stacked gutters, composed of 0.5–1 mm-thick packages of fine-grained sand and silt, oriented concave-up in cross section and intersect burrow floor at 10–15° in profile; burrow walls ornamented with fine, longitudinally directed striae, formed as exterior expression of the spreite.

*Discussion.*—There is some possibility of misidentification of incomplete burrows of *Teichichnus*. It has been noted that *Teichichnus* may be transitional to *Rhizocorallium* (Chisholm, 1970), *Ophiomorpha* (Hester and Pryor, 1972; Frey et al., 1978), and *Thalassinoides* (Frey and Seilacher, 1980). None of these other ichnogenera were collected from the Deadwood Formation, except for one possible specimen of ?*Thalassinoides* from the Little Elk Creek section. Because of the incomplete nature of the collected specimens only a tentative assignment is given to the Deadwood forms.

*Facies.*—KSU 4574 was collected 3.5 m above the base of lithofacies 2. KSU 4682 was collected 8.7 m above the base of lithofacies 1.

Ichnogenus *Thalassinoides* Ehrenberg, 1944
*Thalassinoides* ichnospecies
(Fig. 13D)

*Material Examined.*—A single specimen (KSU 4589) was collected from the Little Elk Creek section.

*Description.*—Cylindrical-shaped burrow system preserved in full relief; burrows oriented horizontal to bedding; incomplete length of main burrow 30 mm; diameter of main burrow 15 mm except at burrow junctions, which swell to 19 mm; secondary burrows slightly smaller than main trunk, diameter 10 mm, oriented at 90° to main burrow; main trunk and secondary bifurcations show regularly spaced constrictions producing an annulated burrow margin; constrictions transverse, slightly arcuate, ranging between 2–5 mm thick in longitudinal direction, grouped two to three annuli per centimeter; internal composition of burrow system different than surrounding matrix. In transverse section burrow cross section oval, with long axis of ellipse parallel to bedding; faint, transverse laminations present, suggesting burrow collapse; bedding of host matrix near burrow system highly disturbed, with top of burrow showing gradational contact with host lithology.

*Discussion.*—Assignment of this specimen to *Thalassinoides* ichnospecies is based on the branching character and slight swelling of the burrow at branch junctions. Burrow junctions of the Deadwood specimen, however, are at nearly 90°, which is atypical of Late Paleozoic and younger forms assigned to this ichnogenus (Myrow, 1995). However, similar T-shaped, rather than Y-shaped, bifurcations have been reported by Howard and Frey (1984), Bromley (1990:159), Maples and Suttner (1990), Myrow (1995), and Uchman (1995). Until recently, *Thalassinoides* had not been recorded from units older than the Ordovician (Sheehan and Schiefelbein, 1984; Bromley, 1990:159; Myrow, 1995). Myrow (1995), however, has identified a new ichnospecies, *T. horizontalis*, from the Upper Cambrian Peerless Formation of Colorado. There are also possible occurrences of *Thalassinoides* in rocks as old as the Lower Cambrian (Droser and Bottjer, 1988). Similarities between the Deadwood *Thalassinoides* and *T. horizontalis* consist of a burrow system oriented parallel to bedding with no vertical shafts, burrow junctions are mostly T-shaped and show little to no swelling, lack of definite scratches along burrow walls, and infilling material that is arranged as spreite that is compositionally different from the host matrix. The Deadwood specimen, however, is larger and exhibits slight constrictions along the margins of interjunction segments.

*Facies.*—This specimen was collected 3 m above the base of lithofacies 3.

Ichnogenus *Trichophycus* Miller and Dyer, 1878
*Trichophycus pedum* (Seilacher, 1955)
(Fig. 14A)

*Material Examined.*—Two specimens (KSU 4554, 4578) were collected from the Deadwood type section. A third specimen (KSU 4543) was collected at Bridal Veil Falls.

*Description.*—Trace preserved in convex hyporelief; consisting of a linear main trunk, ranging from 3–5 mm wide; incomplete length of 65 mm; stout secondary branches arise from midline of main trunk, loop around, and extend upward into host bed; exposed parts of secondary branches not more than 4 mm wide and 6 mm long. Lateral margins of main trunk with faint undulations; margins of secondary branches straight.

*Discussion.*—Geyer and Uchman (1995:185–187, fig. 5.3–5.5, 6, 7.1–7.9) have recently reassigned this form to *Trichophycus* Miller and Dyer, based on differing behavioral patterns between this ichnospecies and other forms of *Phycodes*. *Trichophycus pedum* consists of a straight to gently winding main burrow oriented horizontal to bedding, with a variable number of secondary lateral probes extending obliquely off the main burrow into the host bed. Geyer and Uchman (1995) note that *T. pedum* exhibits variable morphology that ranges from straight to curved main tunnels, coupled with different densities of the secondary probes. The Deadwood forms show a linear tunnel with sparse secondary probes, which closely resemble *T. pedum* collected from the Lower Cambrian Cándana Quartzite of Spain (Crimes et al., 1977:fig. 7a, b), and a few forms collected from sandstone facies of the Lower Cambrian Gross Aub Formation (Geyer and Uchman, 1995: fig. 7.7). The prime similarity is the straight character of the main tunnel in both the Deadwood and Spanish material compared to the more common, gently curving to palmate morphology represented by material from the Lower Cambrian of Pakistan (Seilacher, 1955), other forms from the Nama Group (Geyer and Uchman, 1995), ?Cambro–Ordovician Kellys Island and Little Bell Island formations (Fillion and Pickerill, 1990), Middle Cambrian Oville Formation of northern Spain (Legg, 1985), Lower Cambrian Breivik Formation of Norway (Banks, 1970), and the Lower Cambrian Random Formation of Newfoundland (Crimes and Anderson, 1985). The straight morphology may be a function of the coarse-grained texture of the hosting sediment, as well as the environment of deposition under which these variates were constructed. The Cándana Quartzite and the hosting lithofacies of the Gross Aub and Deadwood formations are medium- to coarse-grained sandstones in association with desiccation cracks that formed under very shallow, intertidal conditions.

*Facies.*—Specimen KSU 4554 was collected 2.5 m above the base, and KSU 4578 was collected 5.9 m above the base of lithofacies 1. KSU 4543 was collected at the base of lithofacies 2.


Fig. 14.—A. *Trichophycus pedum* (Seilacher), KSU 4554, convex hyporelief, lithofacies 1, Deadwood type section. B, C. *Uchirites* ichnospecies. B. Full-relief burrow shown from above, note sharp ridge at apex of burrow; KSU 4573, lithofacies 2, Deadwood type section. C. Same specimen seen in cross section, note blunt lower apex of burrow. D. "Branched Burrow," KSU 4562, convex epirelief, lithofacies 2, Deadwood type section. Bar scales represent 1 cm.

### Ichnogenus *Uchirites* Macsotay, 1967
### *Uchirites* ichnospecies
### (Fig. 14B, C)

*Material Examined.*—A single specimen (KSU 4573) collected at the Deadwood type locality.

*Description.*—Straight tube preserved in full relief; width 10 mm; incomplete length of 15 mm; surface of tube ornamented with faint grooves running parallel to long dimension of trace; trace cross section almond-shaped, with sharp upper apex and blunt lower apex; trace interior hollow, consisting of a circular tube encased in a sheath-like envelope; envelope composed of a coarser-grained material than host lithology.

*Discussion.*—A diagnostic character of *Uchirites* is its almond-shaped cross section, consisting of a sharp upper apex and blunt lower apex. The burrow typically consists of an inner structure with a smooth external surface surrounded by an outer structure having the appearance of a sheath (Chamberlain, 1971:231). In well-preserved specimens this outer sheath typically is ornamented by fine striae obliquely oriented to the midline. Although the Deadwood specimen lacks a striated surface, it shows sufficient morphological characters to be classified under *Uchirites*.

*Facies.*—This specimen was collected 7 m above the base of lithofacies 2.

"Branched Burrow"
(Fig. 14D)

*Material Examined.*—Specimen KSU 4562 was collected from the Deadwood type section.

*Description.*—Narrow, unornamented, branched-burrow system preserved in convex epirelief; main burrow 3.5 mm in diameter; second-order branches 2 mm in diameter, typically at 90° to main burrow; third-order burrows typically 1–1.5 mm in diameter; making a 20–25° angle with second-order burrows.

*Discussion.*—This trace vaguely resembles *Chondrites* Sternberg and *Hartsellea* Rindsberg. Differences between it and *Chondrites* are the higher branch angles and the decrease in burrow diameter in the second- and third-order burrows seen in the Deadwood specimen. *Hartsellea* also represents a branching-burrow system like *Chondrites*, but individual burrows of *Hartsellea* have a distinctly lined wall and internal menisci (Rindsberg, 1994:47–50, pl. 9B, 10A, B, 11A–D, 12C, D). The Deadwood specimen shows no lining or menisci fill.

*Facies.*—This specimen was collected at the top of lithofacies 2.

"Gently Curved Trace"
(Fig. 15A)

*Material Examined.*—A single, incomplete specimen (KSU 4533) collected at Bridal Veil Falls.

*Description.*—Smooth, narrow ridge preserved in convex epirelief. Ridge consistently 1.2 mm wide; circumference is 80 mm, incomplete; ridge gently curves to resemble a half circle.

*Discussion.*—Because this specimen is incomplete no ichnogeneric designation is given, although it does resemble a partial *Circulichnis montanus* Vialov, 1971 (Häntzschel, 1975:W52, pl. 31, fig. 4; Pickerill and Keppie, 1981:fig. 3). The trace does not appear to have been actively backfilled in that the filling material lacks distinct spreite and menisci, and is of the same composition as the host matrix. This excludes the form as a possible *Planolites* burrow based on taxonomic criteria (Pemberton and Frey, 1982; Keighley and Pickerill, 1995). The trace is also unlined, which would exclude it as a possible *Palaeophycus* (Pemberton and Frey, 1982; Keighley and Pickerill, 1995).

*Facies.*—Specimen was collected 1.8 m above the base of lithofacies 3.

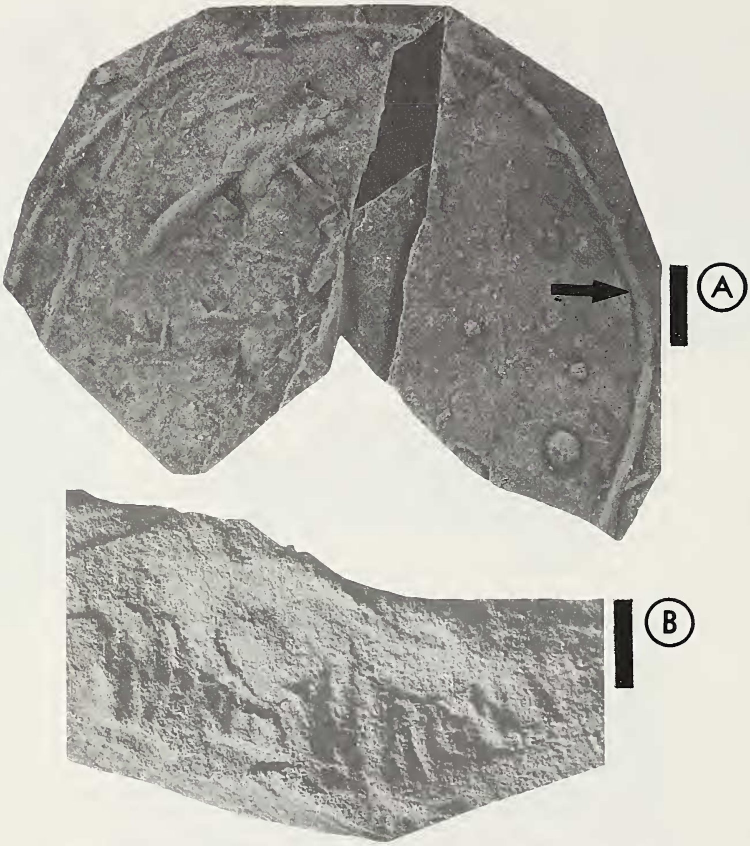



Fig. 15.—A. "Gently Curved Trace" shown by arrow, KSU 4533, lithofacies 3, Bridal Veil Falls section. B. "Ribbed Trail," KSU 4573, concave epirelief, lithofacies 2, Deadwood type section. Bar scales represent 1 cm.

### "Ribbed Trail"
### (Fig. 15B)

*Material Examined.*—A single specimen (KSU 4573) collected at the Deadwood type section.

*Description.*—Slightly curving furrow preserved in concave epirelief; furrow width approximately 20 mm; incomplete length 50 mm; furrow with regularly spaced transverse ridges; ridges consistently 2 mm thick in longitudinal direction, spaced 3 mm apart, and do not extend to lateral margins of furrow.

*Discussion.*—The poor preservation of the specimen does not support a formal ichnogeneric designation. However, the trace looks very similar to the epichnial groove part of *Plagiogmus* Roedel (Glaessner, 1969:385, fig. 8).

*Facies.*—Specimen was collected 7 m above the base of lithofacies 2.

## RESULTS

### *Aspects of Cambro–Ordovician Sedimentation*

Sedimentary structures consisting of bidirectional crossbedding, clay drapes, flaser, wavy, and current-rippled bedding, and the occurrence of mudcracks in siltstone and sandstone beds indicate that lithofacies 1 and 2 were deposited under intertidal conditions (Ginsburg, 1975:92; Klein, 1985). The fine-grained terrigenous clastics intermixed with tempestite-derived intraclastic limestones in lithofacies 3 indicate that this unit was deposited further offshore on the Cambro–Ordovician shelf. The chaotic nature of the intraclasts suggests little postdepositional reworking by tidal currents or waves, implying deposition below normal wave base, but not below storm wave base. The lenticular nature and curved lower contacts of the intraclastic beds suggest scouring of the substratum during tempestite deposition. A similar interpretation was made for Deadwood time-equivalent units in Montana (Emerson Formation) and Wyoming (Du Noir Formation; Sepkoski, 1982), which also consist of interbedded shale and intraclastic limestone.

Other published examples of Cambro–Ordovician siliciclastic tidal deposits include the Eureka Quartzite of California and Nevada (Klein, 1975), the Monkman Quartzite of western Canada (Jansa, 1975), the Hickory Sandstone of central Texas (Cornish, 1986), the Theresa-March formations of New York and Ontario (Bjerstedt and Erickson, 1989), the upper Bell Island and Wabana groups of Newfoundland (Fillion and Pickerill, 1990), and the Santa Rosita Formation of Argentina (Mángano et al., in press). Except for the Bell Island and Wabana groups, all of these formations conform lithologically and texturally to the Deadwood–Aladdin tidal deposits. Similarity among these regionally separated deposits is illustrated by the lack of terrigenous mud in the upper intertidal to supratidal regimes. In contrast, Late Paleozoic (Carboniferous) to Recent tidal environments contain a predominance of mud in upper tidal facies (Ginsburg, 1975; Weimer et al., 1982; Klein, 1985); because tidal-flat facies models have been based on these Recent mud-dominated tidal sequences, recognition of Lower Paleozoic tidal deposits have been difficult (Dott and Byers, 1980; Klein, 1980; Moiola, 1980). For example, units previously interpreted as simple blanket sands that formed under wave-dominated coastal systems such as the Middle Cambrian Flathead Sandstone of Wyoming and Montana, the Lower Ordovician St. Peter Sandstone of the mid-continent, and the Mt. Simon and Eau Claire formations of Wisconsin exhibit a greater complexity and intergradation of tidal and nonmarine fluvial sedimentation than previously reported (Dott and Byers, 1980; Moiola, 1980; Driese et al., 1981; Bjerstedt and Erickson, 1989).

Lack of a dominant mud facies in these Cambro–Ordovician tidal orthoquartzite suites may be due to the extreme macrotidal range of the Cambrian epeiric seas, coupled with an absence of vascular plants. Given the low-lying topography of the Precambrian basement during the initial Cambrian transgressions onto the craton, frictional drag would have minimized wave processes while augmenting tidal ranges and currents in nearshore coastal settings (Irwin, 1965; Schopf, 1980; Hallam, 1981; see Fig. 2). Assuming horizontal time lines in Figure 4, a minimal breadth of the Black Hills Cambro–Ordovician shelf intertidal zone may have approximated 25–35 km, which far exceeds the 7-km average of modern macrotidal coasts (Klein, 1980; Weimer et al, 1982). The closest modern analog that can be compared to the Deadwood–Aladdin intertidal zone is the Yellow Sea macrotidal flat of southwestern South Korea, with a tidal-flat width ranging from 8–25 km (Klein, 1980; Alexander et al., 1991). Current energy produced by tidal forces was probably fairly strong, especially across shelf areas within effective wave base. Lithofacies 2 is interpreted as forming in a moderate- to high-energy tidal regime due to the occurrence of parting lineations on some siltstone and sandstone bedding surfaces, and probably falls within the high-energy region of Irwin's model for epicontinental seas (Irwin, 1965; Hallam, 1981; see Fig. 2). Current energy probably slackened over the inner parts of the tidal flats, exemplified by lack of well-developed bedforms and tidal sedimentary structures in lithofacies 1, compared to lithofacies 2. Lack of fine-grained terrigenous clastics in lithofacies 1 suggests that tidal energy was strong enough to wash all but a coarser-grained sand fraction basinward. Transportation of muds basinward was also permitted by the lack of baffling by vascular plants in the upper intertidal and supratidal zones during the Early Paleozoic. Tidal deposits in Texas and New York also exhibit a coarsening of grain size in the upper peritidal to supratidal parts of the sand flats (Cornish, 1986; Bjerstedt and Erickson, 1989). Except for thin shale partings and clay drapes in lithofacies 2, the mud fraction by-passed the intertidal zones, and was deposited further offshore in lithofacies 3 (Fig. 16).

Besides their trapping effects of fine-grained siliciclastics in upper tidal areas, the importance of vascular plants today can be inferred by changes in the type of physical and chemical weathering in terrestrial environments throughout geologic time. Without terrestrial plants, eolian processes probably dominated land areas in the Early Paleozoic, and without the stabilization effects of plants, would have deposited a greater amount of coarse-grained sand in nearshore marine environments than observed today (Dott and Byers, 1980). At least for terrigenous tidal deposits, tidal sedimentation has changed since the Cambrian, and may be directly or indirectly related to the exploitation of the inner tidal zone by vascular plants, and strong tidal currents prevalent along ancient mesotidal coasts.

The nature and trophic structure of tidal-flat benthic communities also must have changed with the evolution of vascular plants because of the indirect effect on substrate type within Cambro–Ordovician upper intertidal regimes. Modern macrotidal flats such as the Yellow Sea coast of South Korea and Gulf of California are characterized by large numbers of epifaunal, herbivorous grazers and deposit feeders in the inner tidal environments (Thompson, 1968, 1975; Frey et al., 1987; Fürsich and Flessa, 1987). Herbivorous gastropods and bivalves dominate these modern peritidal and supratidal environments, feeding on algae and plant detritus deposited from suspension from waning tidal currents (Fürsich and Flessa, 1987). Consequently, there is a preponderance of epifaunal repichnia- and infaunal vertical domichnia-type traces in Recent upper tidal regimes (Frey et al., 1987). Traces common to the upper tidal zones of the Deadwood Formation differ considerably from the modern counterparts (Table 1). Horizontal infaunal burrows are the most common traces found. These assemblages are dominated by *Planolites*, with minor occurrences of *Palaeophycus*, *Trichophycus*, and ?*Teichichnus*. Although vertical domichnia burrows are present in the upper tidal flats, they are subordinate to the horizontal burrows. Also contrary to Recent tidal assemblages, repichnial surface trails are noticeably sparse in the upper sand flats of the Deadwood (lithofacies 1). However, repichnion do increase in diversity and density in the outer sand-flat deposits (lithofacies 2). A similar situation occurs in the Cambro–Ordovician Marsh-Theresa tidal deposits as the epifaunal–infaunal ratio increases from peritidal to lower intertidal deposits (Bjerstedt and Erickson, 1989) and in the Ordovician Santa Rosita Formation of Argentina, which is characterized by a monoichnospecific *Planolites montanus* trace-fossil assemblage in the most shoreward tidal facies (Mángano et al., in press).

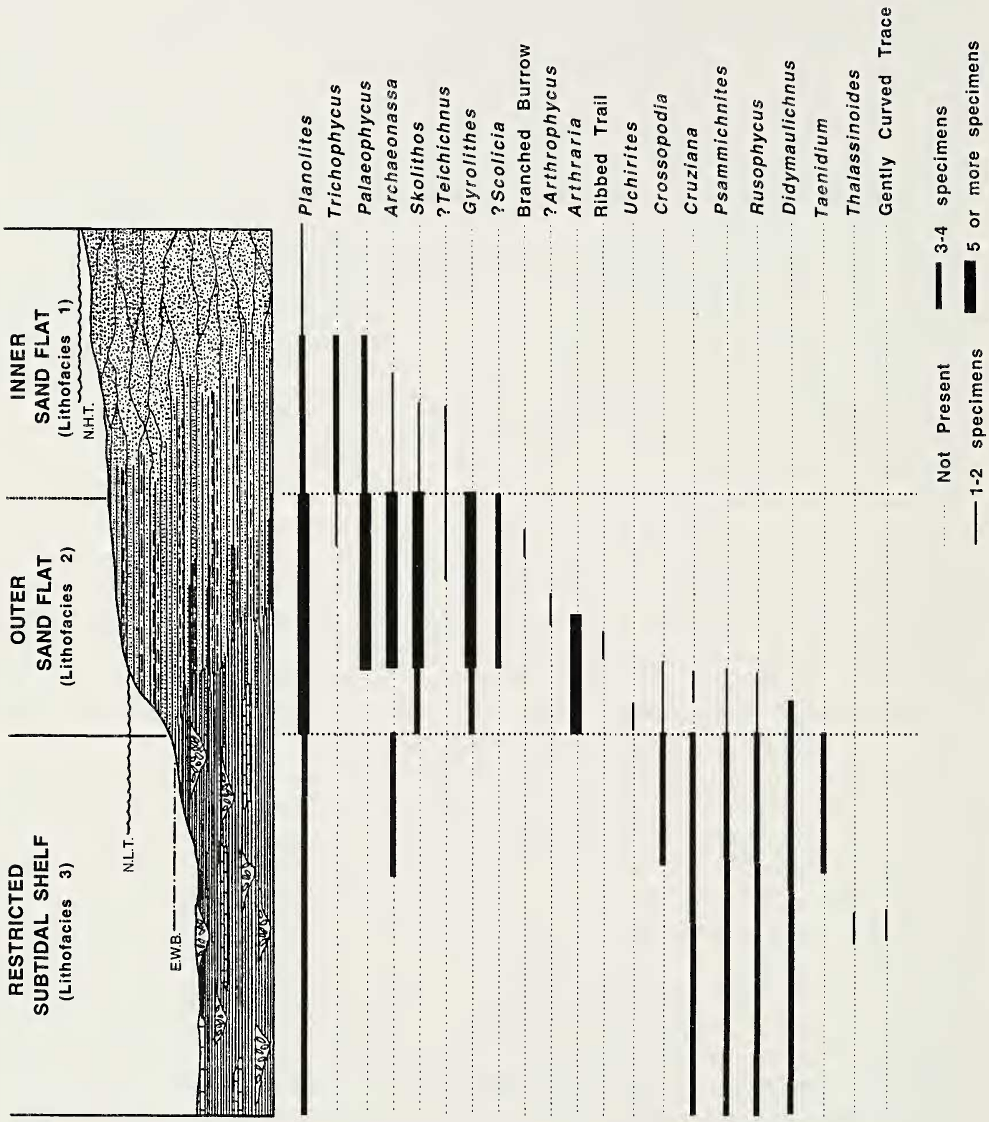
*Trace-fossil Assemblages*

When coupled with the Deadwood and Aladdin lithofacies, the trace-fossil assemblages provide a clearer picture of Cambro–Ordovician nearshore paleoenvironments. The Deadwood–Aladdin trace fossils can be segregated into distinct assemblages related to the hydrodynamic and sedimentological conditions that persisted during the Cambro–Ordovician of the Black Hills. These assemblages also recur within their prescribed lithofacies during repeated shifting of strand lines (Fig. 4, 16). Two basic trace-fossil assemblages dominate: 1) an intertidal sand-flat assemblage that occurs in lithofacies 1 and 2, and 2) a restricted subtidal-shelf assemblage corresponding to lithofacies 3. Trace fossils also reflect sedimentologic and taphonomic regimes within the intertidal environment, and can be segregated into an inner sand-flat assemblage (traces enclosed in lithofacies 1) and an outer sand-flat assemblage (traces enclosed in lithofacies 2). Table 1 summarizes the trace fossil distribution with corresponding lithofacies types.

*Inner Sand-flat Assemblage.*—This assemblage is characterized by very low ichnofaunal density and diversity, and occurs in lithofacies 1 and shoreward parts of lithofacies 2 (Table 1; Fig. 16). Ichnotaxa are dominated by *Planolites*. *Palaeophycus*, *Skolithos*, *Trichophycus*, and ?*Teichichnus* also occur, but are rare and normally found in the offshore parts of the assemblage (Fig. 3, 16).

The paucity of trace fossils observed in these inner sand flats contrasts with modern tidal flats, which normally show low diversity but high density of traces within the inner-tidal regimes (Weimer et al., 1982; Ekdale et al., 1984:177; Frey et al., 1987). Environmental parameters such as salinity, temperature, current energy, and subaerial exposure probably varied greatly within these inner-tidal regimes as they do in modern environments, and probably influenced the number and distribution of the trace fossils. Also important are the potential taphonomic effects inherent in very nearshore marine settings (Bromley, 1990) in that the ichnological distinction between the inner and outer sand-flat assemblages may be as dependent on taphonomy, particularly depth of burrowing, as it is on the varying environmental conditions across the intertidal zone.

Although there are noted exceptions in the depth and degree of bioturbation for Lower Paleozoic rocks (Miller and Byers, 1984; Sheehan and Schiefelbein, 1984), burrowing depths of the Cambro–Ordovician marine benthos were shallow (Ausich and Bottjer, 1982, 1990, 1991; Thayer, 1983; Bottjer and Ausich, 1986) and confined to the uppermost mixed-layer tiers (Bromley, 1990:128; Bromley and Asgaard, 1991). Shallow trace construction is also common in modern intertidal environments (Frey et al., 1987). Added to the preponderance of shallow traces, Frey et al. (1987) noted that few of these epibenthic traces in the shoreward parts of the Yellow Sea tidal flats would have little potential for being preserved. It stands to reason that most biogenic activity in the Deadwood inner sand-flat regime stood a fairly poor chance of being preserved as well. The prevalence of disrupted bedding associated with the Deadwood inner sand-flat trace-fossil assemblages may indicate that intense bioturbation occurred without subsequent preservation of discrete, recognizable trace fossils. When comparing the type and distribution of ichnotaxa between the inner and outer sand-flat assemblages, ichnofaunal differences are not as much a change in ichnotaxa, but an exclusion of inferred, shallowly constructed biogenic structures. Full-relief burrows of *Planolites*, *Palaeophycus*, and *Skolithos* are the most common traces in the inner sand-



RESTRICTED SUBTIDAL SHELF (Lithofacies 3)
OUTER SAND FLAT (Lithofacies 2)
INNER SAND FLAT (Lithofacies 1)
N.H.T.
N.L.T.
E.W.B.
Planolites
Trichophycus
Palaeophycus
Archaeonassa
Skolithos
?Teichichnus
Gyrolithes
?Scolicia
Branched Burrow
?Arthrophycus
Arthraria
Ribbed Trail
Uchirites
Crossopodia
Cruziana
Psammichnites
Rusophycus
Didymaulichnus
Taenidium
Thalassinoides
Gently Curved Trace
Not Present
1-2 specimens
3-4 specimens
5 or more specimens

flat assemblage. It is only toward the more offshore parts of the assemblage that shallower trace fossils such as *Archaeonassa* are preserved (Table 1; Fig. 3, 16).

Substrate type also would have been a factor in trace-fossil preservation, particularly the grain size of the hosting medium. The fact that the lithofacies associated with this assemblage is coarser grained and monotextured compared to the outer sand-flat lithofacies would have contributed to the subtle ichnological and taphonomic differentiation of the intertidal assemblages. The course texture of the sediment common to the inner sand flats may have led to the exclusion of other ichnospecies of *Palaeophycus* (besides *P. tubularis*) where taxonomic criteria are based on the delicate ornamentation of the burrow lining, which may not have been preserved in the coarser sediment.

Environmental parameters like current energy, oxygenation, and salinity also played an important role in defining the character of the inner sand-flat assemblage. What is apparent in Figures 3 and 16 is the presence of complex fodinichnia like ?*Teichichnus* and *Trichophycus*, and epichnia like *Archaeonassa* in the more offshore, and assumed more normal, marine parts of the assemblage. Absence of these trace fossils in shoreward parts of the assemblage is probably due to an environmental gradient occurring perpendicular to depositional strike.

Ecological stress acting across the inner-flat benthos is also implied by the average size of the preserved ichnotaxa compared to those same ichnotaxa in the outer flat. Modern outer- and inner-flat areas, such as in the Gulf of California, exhibit a shoreward decrease in size of organisms, particularly mollusks, inhabiting both tidal regimes (Fürsich and Flessa, 1987). Inner-flat gastropods and bivalves were considerably smaller, even within the same species, than their outer-flat counterparts (Fürsich and Flessa, 1987). The authors did not have a definitive explanation for this phenomenon, but stated it could be attributed to either the ecological factors inherent of the stressful inner-flat environments, or to waning current energy across this nearshore area that transported only the smaller species from the outer flat. Within the Deadwood Formation, *Planolites* occurred with high frequency in all lithofacies, represented by *P. montanus* and *P. beverleyensis*. Ichnospecific distinction of these two forms is based primarily on the size of the specimens. *Planolites beverleyensis* has trace diameters 5–8 mm larger than *P. montanus* (Pemberton and Frey, 1982). In all measured sections, *P. montanus* was the only *Planolites* ichnospecies collected from lithofacies 1, suggesting that larger forms of the *Planolites*-producing animal were excluded from inner sand-flat environments. A similar situation occurs in the Lower Ordovician Santa Rosita Formation in Argentina, where high intertidal lithofacies consist of monoichnospecific trace-fossil assemblages of *P. montanus* (Mángano et al., in press). Trace-fossil assemblages in the offshore parts of the intertidal zone of the Santa Rosita show a greater degree of trace-fossil complexity and diversity compared to the *P. montanus* assemblage. This contrast between inner and outer tidal-flat trace-fossil assemblages appears similar to the transition between lithofacies 1 and lithofacies 2 of the Deadwood Formation, and indicates similarities between many Cambro–Ordovician intertidal deposits. Size trends are also observed in burrows of *Pa-*

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←

Fig. 16.—Lateral distribution of collected ichnogenera and environments of deposition during time T of Figure 4. No vertical or lateral scale is implied. N.H.T. and N.L.T. represent normal high tide and normal low tide, respectively. E.W.B. represents effective wave base.

*laeophycus tubularis*, which are 7 mm smaller in diameter in lithofacies 1 as compared to lithofacies 2 (see discussion under *Palaeophycus tubularis* in Systematic Ichnology). Differences in the size of trace fossils also were noted by Hakes (1985) from Upper Pennsylvanian marginal-marine settings of Kansas. Hakes (1985:31, table 2) showed that many of the trace fossils from nearshore brackish-water facies were much smaller than those same trace fossils from normal marine facies. This decrease in size was attributed to variable salinities encountered in the marginal-marine trace-fossil assemblages, which probably inhibited the trace makers from attaining full adult size.

It seems unlikely that selective destruction of larger burrows contributed to the size differences between the outer sand-flat and inner sand-flat trace fossils. The analogy can then be drawn between the Deadwood intertidal assemblages and those exhibited by bivalves and gastropods from the Gulf of California, suggesting that size variability in taxa across the intertidal zone is due to ecological factors.

*Outer Sand-flat Assemblage.*—Ichnotaxa diagnostic of this assemblage includes *Archaeonassa*, *Skolithos*, *Gyrolithes*, ?*Scolicia*, *Arthraria*, and *Planolites beverleyensis* (Table 1; Fig. 16). This assemblage is characterized by an increase in numbers and diversity of ichnogenera compared to the inner sand-flat assemblage. Endobenthic domichnia and fodinichnia of *Palaeophycus*, *Skolithos*, *Planolites*, and *Trichophycus*, and repichnion of *Archaeonassa* increase markedly. New ichnotaxa represented by domichnia (*Arthraria*) and fodinichnia (*Psammichnites*, *Gyrolithes*, and ?*Scolicia*) are also encountered, and indicate more epibenthic and shallow endobenthic modes of life. Trilobite cubichnion and repichnion in the form of *Rusophycus* and *Cruziana* also occur, but are relegated to the more offshore parts of the assemblage. Stronger current action and more normal-marine open circulation, implied by the presence of planar laminations and current-rippled bedding surfaces, accompanies the increased ichnogeneric diversity. The combination of normal-marine circulation and tidal-dominated primary sedimentary structures suggest that this trace-fossil assemblage inhabited an offshore, moderate- to high-energy part of the tidal flat.

Preservational acuity of the different ethological trace fossils increases in the outer sand-flat assemblage, and is directly related to increased sediment heterogeneity found in lithofacies 2. Important to the preservation of surface and near-surface biogenic structures would have been clay drapes deposited from waning tidal currents. These clay drapes, represented as thin shale partings and flaser bedding, would have protected the epichnial and shallow endichnia from erosion at times of exposure and resubmergence of the assemblage during the transition from low to high tide. Conversely, lack of an appreciable mud or fine-grained sand component in the inner sand-flat environment probably contributed to the poor preservational quality of that assemblage.

A strong ecological gradient still occurred across the outer sand flats as *Rusophycus* and *Cruziana* only occur in the offshore parts of the assemblage (Fig. 3, 16). Lack of these ichnogenera in the more landward parts of the outer sand flat suggests that environmental conditions were still too hostile for normal-marine trilobites. Other ichnogenera that overlap from the lower energy areas of the subtidal zone include *Crossopodia* and *Didymaulichnus* (Fig. 16), and imply that environmental conditions were more hospitable for their trace makers toward the offshore parts of the sand flats.

Both the outer and inner sand-flat assemblages represent a mixed or overlapping *Skolithos–Cruziana* ichnofacies. Displacement or total absence of a particular ichnofacies from the archetypical ichnofacies model has been well documented (Ekdale, 1988; Bromley, 1990; Frey et al., 1990). A notable example for a modern tidal flat is from the Yellow Sea, which falls entirely within the *Cruziana* ichnofacies, with no *Skolithos* ichnofacies shoreward (Frey et al., 1987). A mixed ichnofacies is commonly found in modern and ancient environments that exhibit fluctuating depositional and taphonomic conditions, such as intertidal and estuarine environments (Ekdale et al., 1984:172, 179; Ekdale, 1985; Bjerstedt, 1988). Within the outer sand-flat assemblage current energy was probably the most variable environmental parameter. Strong currents suggestive of bed-load transportation are implied by the presence of parting lineations, cross-bedding, and current-rippled bedding surfaces, while the presence of shale partings and flaser bedding implies suspended-load deposition from waning tidal currents. The net result is a mixed trace-fossil assemblage and taphonomic signature characterizing both high and low current energy.

*Restricted Subtidal-shelf Assemblage*.—This trace-fossil assemblage corresponds to lithofacies 3 (Fig. 3, 16). Cubichnia and repichnia (*Rusophycus* and *Cruziana*) dominate and are the most diagnostic ichnotaxa of this assemblage. Other ichnotaxa include repichnion of *Archaeonassa* and *Didymaulichnus*, and fodinichnia of *Taenidium*, ?*Arthrophycus*, *Planolites*, *Psammichnites*, *Crossopodia*, and *Thalassinoides* (Table 1; Fig. 16). The presence of fine-grained terrigenous and carbonate sediments, well-developed, thin to fissile bedding, coupled with epibenthic cubichnia and repichnia suggests that this facies formed in a subtidal, normal-marine environment characteristic of the *Cruziana* ichnofacies. Siliciclastic deposition was sporadic, allowing deposition of carbonate sediment during times of low siliciclastic influx. Periodic storms eroded carbonate sediment from peritidal banks to the west (Fig. 2) and redeposited the flotsam as lenses of intraclastic limestones. Little or no wave reworking is evident in the intraclasts, indicating that this lithofacies formed below normal wave base but not below storm wave base.

Previous paleoecological studies interpreted this lithofacies as forming on intertidal mud flats (Lochman-Balk, 1964, 1970, 1971; Lochman-Balk and Wilson, 1967). However, the taphonomy of the preserved trace fossils, characterized by finely preserved epibenthic and shallow endobenthic traces, coupled with the chaotic nature of the intraclastic limestones, contradicts an intertidal interpretation of this lithofacies. The high diversity but low abundance of traces characteristic of this assemblage suggests periodic disruption of the normal-marine benthos. Low abundance of trace fossils is an ecological response of the benthic community to storm surges that inhibited the establishment of well-developed communities in the substrate. A similar association was noted by Pemberton and Frey (1984) and Vossler and Pemberton (1988) for mixed quiet-water and tempestite deposystems in the Upper Cretaceous of Alberta.

One apparent irregularity of this assemblage is the low density of endobenthic fodinichnia compared to the outer sand-flat assemblage. The lack of strong bioturbation is documented by the well-developed fissility of the shales and absence of burrow mottling in the micritic limestones. The absence of large numbers of infaunal traces may also have be a response to tempestite deposition, but it seems more likely due to hardground or firmground development, which tends to decrease endobenthic activity and trace fossil diversity (Ekdale, 1988). Hardground to firmground development on intraclastic limestones and on some micritic limestone beds is suggested by the presence of expansion cracks on limestone bedding surfaces formed during early cementation, as well as by protrusion of intraclasts above bedding. The environmental interpretation of subtidal deposition coupled with early cementation in this lithofacies is also supported by Myrow (1995), who noted a strong correlation between the ichnogenera *Thalassinoides* and firmground to hardground development. *Thalassinoides* also appears to be restricted to intertidal and shallow subtidal environments of deposition. Although *Thalassinoides* is not common in this assemblage, its presence strengthens the interpretation that hardground development may have played a part in restricting bioturbation and trace-fossil density. Hardground development is not unique to this lithofacies, and has been documented from similar units in Montana and Wyoming (Brett et al., 1983).

## CONCLUSIONS

Combining lithostratigraphic and ichnologic data is an extremely effective aid in deciphering Deadwood–Aladdin paleoenvironments. Sedimentological and hydrodynamic responses of the enclosed ichnotaxa allowed for segregation of intertidal deposystems into two assemblage zones, an inner and outer tidal flat. Due to the extreme changes in environmental and taphonomic parameters, the trace-fossil assemblage enclosed in the inner-flat environment is characterized by low ichnofaunal diversity and abundance. Parameters such as salinity, water temperature, current energy, and sediment heterogeneity greatly influenced the character of this assemblage. Key ichnotaxa that differentiate the outer sand flat from the inner sand flat include: *Archaeonassa*, *Skolithos*, ?*Scolicia*, *Gyrolithes*, *Arthraria*, and *Planolites beverleyensis*. Taphonomic characteristics, as well as changes in the size of the preserved trace fossils, can also be used as guides in segregating the intertidal assemblages.

The subtidal shelf assemblage is characterized by an increased number of shallow repichnia and cubichnia compared to the intertidal assemblages. Main environmental controlling factors on this assemblage appear to be frequent tempestite deposition that may have temporarily disrupted the quiet-water benthos. Lack of deep burrowing ichnofauna within this assemblage may also have been due to the periodic storms that would have exposed firmground or hardground surfaces, and inhibit deep infaunal burrowing.

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